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CATEGORIZATION AND CHARACTERIZATION OF AMERICAN DRIVING CONDITIONS (Phase I)

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16. Abstract The objectives of this study were: (1) develop a multidimensional matrix as an analysis framework to classify travel of personal motor vehicles according to fuel consumption, (2) to identify and assess available information on travel and fuel consumption, and (3) to describe how to use specific information for quantifying the matrix. A review of the fuel economy literature revealed a large number of factors which influence fuel consumption. Only some of these factors were related to driving conditions. The factors categorizing driving conditions were selected according to their independence, their relationship to fuel consumption, and their interest for studying fuel economy policies. They are: trip purpose, trip length, time, geographic area, highway class and vehicle class and model year. Fuel consumption rates can be estimated from vehicle and trip characteristics including trip length, ambient temperature and average trip speed. These last two factors are not dimensions of the matrix but are, on the average, determined by certain dimensions: time, geographic area, highway class, and trip length. Currently available sources of vehicle travel information are not sufficiently detailed to disaggregate VMT according to the selected factors. However sufficient basic data are available to estimate VMT under the selected driving conditions. The most detailed information was collected by the 1977 NPTS. Other information is regularly collected by traffic counting programs, and by motor vehicle inspection programs in certain states. An approach was outlined to estimate VMT from these sources, disaggregated according to the factors characterizing driving conditions. Potential errors of the estimates were estimated. Promising statistical methods for quantifying the matrix were identified; however, some aspects of estimating error can not be addressed without an analysis of the actual data. A plan for implementing this methodology is presented. Illustrative examples of a scaled down matrix and its use are presented in appedices.

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PREFACE

The authors, Dr. Joksch and Mr. Reidy, would like to acknowledge the many individuals and organizations which have contributed to this study. Firstly, there is the Transportation Systems Center's support and the involvement, attention and guidance of Dr. Stephen Huntley, the Contract Technical Monitor. Secondly, we wish to recognize the many organizations which directly aided us in gathering and understanding the diverse (and often, the most recent) information on motor vehicle travel and fuel consumption. Foremost among these are the Federal Highway Administration (especially the Planning Services Branch) and the Motor Vehicle Manufacturers Association. Several of the governmental agencies were contacted by CEM for information including: The U.S. Bureau of the Census, Environmental Protection Agency, Department of Energy, Oak Ridge National Laboratory, The National Cooperative Highway Research Program, and several state DOTs, including especially Connecticut and New York. In the private sector, the authors had contacts with technical staff from the major automotive manufacturers, especially General Motors. Finally, there are the other researchers in the Automotive Fuel Economy Research and Analysis Program with whom we have shared information.

This report would not be possible without the substantial contribution of CEM staff and consultants. In particular, Mr. Diccon Bancroft has provided substantial support on many questions relating to the accuracy of travel estimates. On this issue of estimation, Dr. Michael Sutherland, assistant professor of statistics at Hampshire College, has provided special assistance. In addition to information from both public and private sources on factors affecting fuel consumption, CEM has had two consultants--Dr. Boris Onuf and Dr. James Hodges, respectively professor and assistant professor of mechanical engineering at the Hartford Graduate Center. Finally, the authors wish to acknowledge the skill, patience and care with which Ms. Kayla Costenoble, Ms. Lin Van Dine, Ms. Marjorie Wallace and Ms. Teri Mayer have prepared this manuscript (and its many previous versions), and Mrs. Janina Peczerski for collecting much of the information. Lastly, the authors retain the responsibility for remaining (and inevitable) shortcomings of this report.

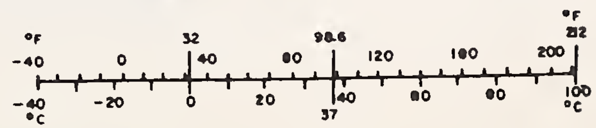
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

Objectives

The objectives of this study were to:

- Categorize driving conditions of personal motor vehicles into a multi-dimensional matrix which shows under which conditions how much driving is done, how much fuel is used under the various conditions, and how efficiently fuel is used under these conditions, as a basis for studying the potential fuel savings resulting from a variety of fuel economy measures.

- Identify currently available information on driving under various conditions and assess its usefulness and reliability.

- Determine how currently available information can be used to quantify the matrix, and which additional data are needed to do this.

Also, a plan for actually quantifying the matrix was to be developed.

Factors Influencing Fuel Consumption

Literature was reviewed to determine what factors influence fuel consumption. A large number of various factors were found which influence fuel consumption directly and indirectly. The more important factors and how they influence fuel consumption are:

Torque (horsepower) and engine speed (rpm) together determine ultimately the fuel consumption of a given engine.

Speed. Instantaneous speed determines the various friction losses, and air resistance. Average trip speed also influenced by changes in speed, is empirically closely related to fuel consumption.

Acceleration and deceleration patterns, including the frequency of stops, determine the work necessary to move the vehicle.

Traffic volume has no direct effect, but it influences travel speed and change patterns.

Highway surface and surface material, as well as ice, snow, and gravel have an effect.

Grades. Energy is used to go uphill; only some of which will be retrieved when going downhill. Also, grade influences speed patterns.

Curvature influences fuel consumption because energy is needed to change the direction, and also because it may result in speed changes.

Geographical area determines temperature and wind patterns and air pressure, and grades and curvature of highways differ between regions.

Wind. Headwinds and tailwinds may have cancelling effects but crosswinds do have the same type influence as curves.

Trip length has a strong influence on fuel consumption because of the warm-up effect on the engine and lubricants in the drive train. Also, trip length influences the selection of highway type and thereby average speed of a trip.

Ambient temperature affects fuel consumption in two ways: it determines the temperature of the intake air and influences the viscosity of lubricants. Also, it has a scaling effect because volume of fuel depends on temperature.

Time--time of the day, day of the week, week of the year--has indirect effects, because it is related to ambient temperature, and it determines traffic patterns which influence travel speed.

Figure 1 shows how these various factors (and a few additional ones) influence fuel consumption directly or indirectly.

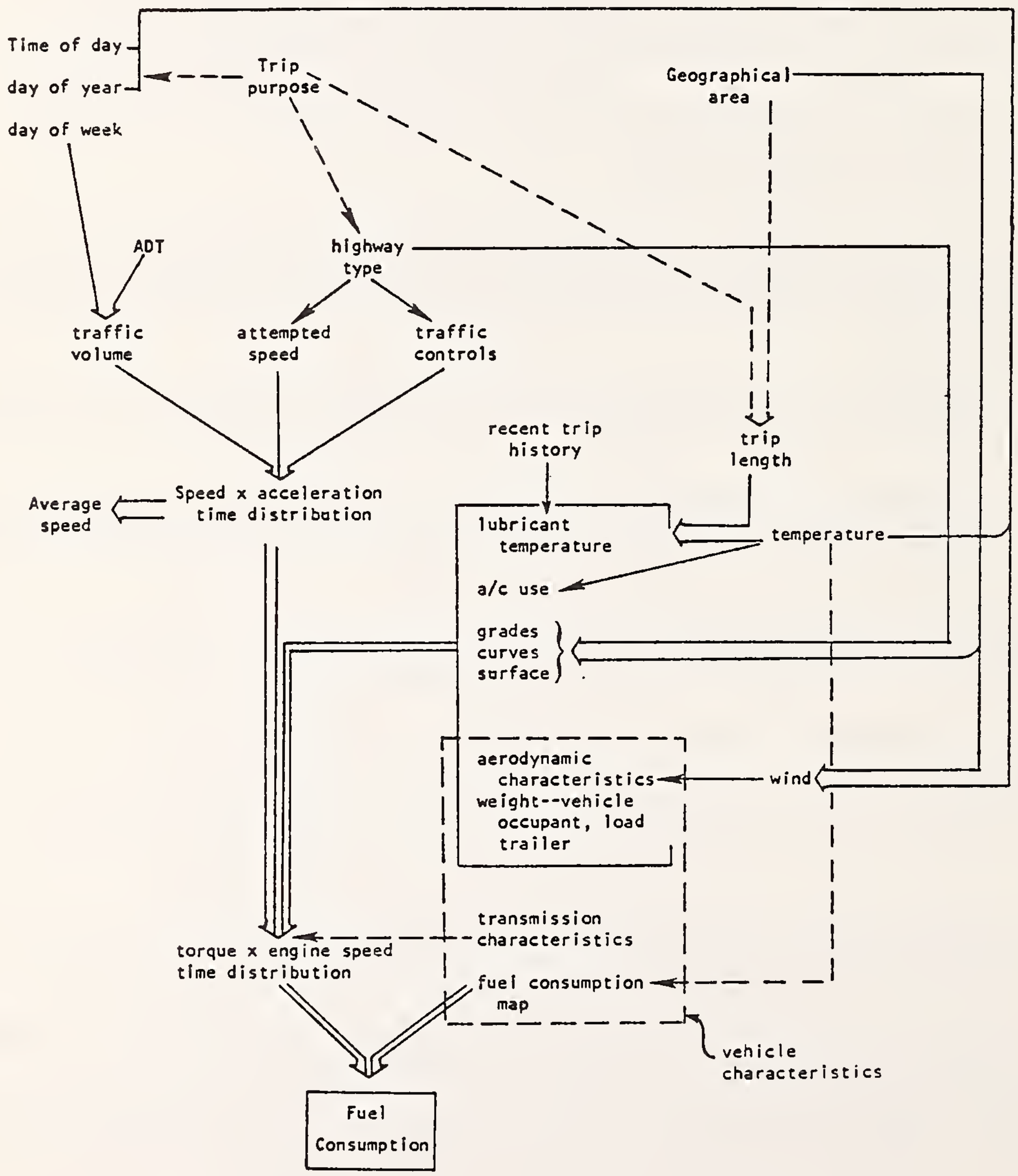

Figure 1

Factors Describing Driving Conditions

First, the factors influencing fuel consumption are not necessarily those which can be influenced by policy measures. Secondly, many factors are related to one another and thirdly, not all factors have the same degree of influence. Factors which appear most important for constructing a usable matrix are:

Trip purpose, which influences the time a trip is taken, its length, to some extent the highway class chosen, and to some extent speed. Also, it is likely to be most influenced by policy measures.

Trip length, which influences the degree to which the vehicle becomes warmed up and reaches optimium fuel economy.

Time, of the day, day of the week, and week of the year (or month or season), which determines the traffic environment, and to some extent ambient temperature.

Geographical area, which influences trip length, climatic conditions, and to some extent highway conditions.

Highway class, which is related to traffic volume and travel speed, and also determines grades and curves.

Vehicle characteristics, of which the most important are vehicle class (often sufficiently approximated by weight) and model year.

These factors were selected as dimensions for a matrix characterizing driving conditions. To be useful for studying their influence on fuel consumption, their relation to the factors directly influencing fuel consumption has to be known. Figure 2 shows the most important relations. It was determined that sufficient information exists to quantify these relations in general terms. However, many relations are known with limited accuracy, and most interaction effects are unknown.

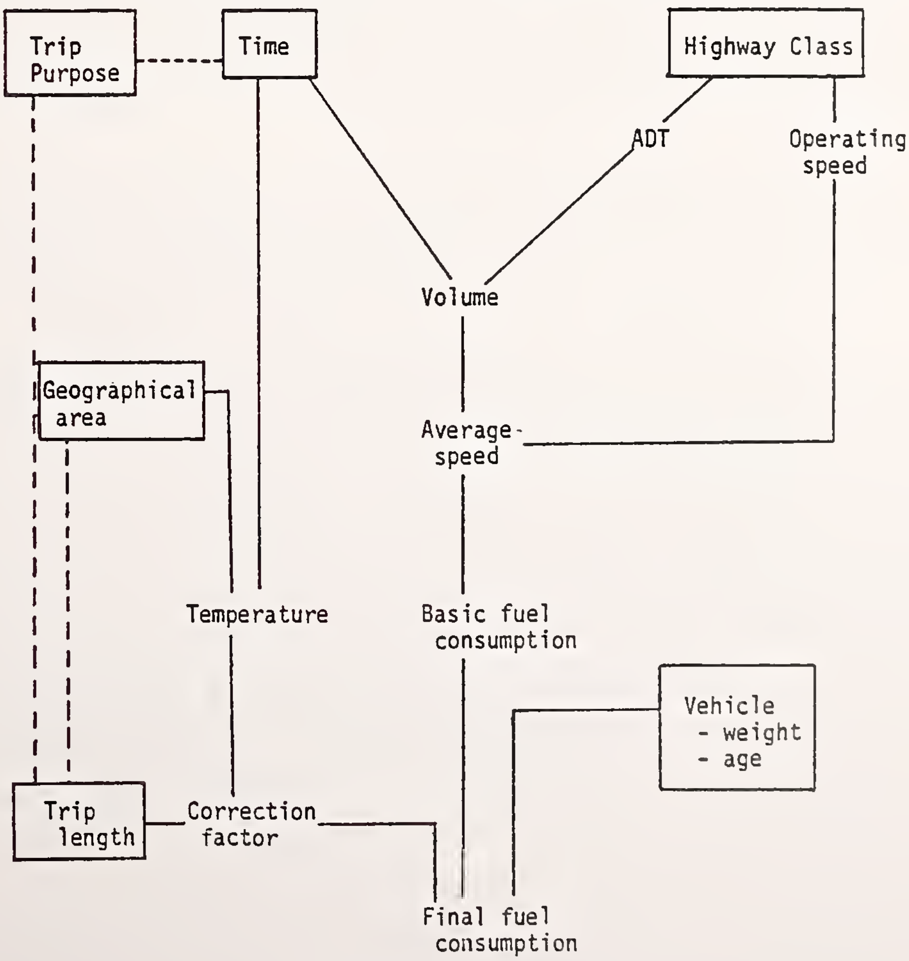

Figure 2

Available Sources of VMT Information

The generally used estimates of vehicle miles of travel are annually published by the Federal Highway Administration. They are disaggregated by vehicle type, or by state and highway system. The figures are compilations of data submitted by the states. Estimation methods differ between the states. The estimates are based on vehicle counts, and/or on fuel sales data. Estimates based on vehicle counts can be quite reliable, but we conclude that in reality the aggregate estimates may have errors of the magnitude of 5 to 10 percent. Estimates based on fuel use are likely to be much less reliable because even average fuel consumption estimates can be wrong by 10 percent.

Other sources of VMT information limited to few time periods are the 1969 Nationwide Personal Transportation Study , and several analyses of automobile odometer readings.

Overall, readily available VMT information is of insufficient detail, and of limited reliability. It is unlikely that a useful matrix can be developed on this basis.

Potential Sources of VMT Information

The following sources of basic data from which VMT information can be derived have been identified:

- The 1977 Nationwide Personal Transportation Study.
- State Continuous Vehicle Counting Programs.
- State Motor Vehicle inspection cards containing odometer readings.

None of these sources provides all the information required, but together they can be used to estimate the desired information. Figure 3 shows by which factors (corresponding to dimension of the matrix) the data from the three sources can be organized.

Dimensions of Matrix	Source of Information		
	NPTS	Vehicle Counts	Odometer Readings
Trip Purpose	X		
Trip Lengths	X		
Time	X	X	
Highway Class		X	
Geographical Area	X	X	X
Vehicle Age	X		X
Vehicle Class	X	(X)	X

Figure 3

The combination of the three marginal matrices, and possibly vehicle registration data, into one comprehensive matrix, can be done by statistical procedures known as "iterative proportional fitting."

This process can be consistently applied only to 1977 data. Until the next NPTS, or other comparable data collection effort, the only up-to-date information can be derived from vehicle counts and odometer readings. However, as a practical matter, one can combine the 1977 NPTS data with more up-to-date information from other sources to extrapolate to different time periods.

Estimating Fuel Consumption Rates

Fuel consumption rates differ between the cells of the matrix, except those cells differing only by trip purpose. The fuel consumption rate is approximately determined by (1) vehicle class (weight), (2) model year, (3) trip length, (4) ambient temperature, and (5) average speed. The last two factors are not dimensions of the matrix, but they are, on the average, determined by other factors: time, geographic area, highway class and trip length.

The influence of the first five factors has been studied by the automobile manufacturers, U.S. Department of Energy, Environmental Protection Agency, U.S. Department of Transportation and others. The accuracy of many findings, especially for older vehicles is limited, and interactions have generally not been studied. Currently, the accuracy of fuel consumption figures is limited, even if measured under ideal conditions, to about 5 percent. A thorough analysis of the existing body of knowledge is necessary to determine fuel consumption as a function of these parameters.

The second problem is to estimate how average ambient temperature and trip speed depend on the dimensions of the comprehensive matrix. The first can easily be done on the basis of climatological data. The second demands a thorough analysis of traffic engineering information, and some aspects may remain speculative.

How to Use the Matrix

Corresponding to the matrix containing VMT estimates, are two other matrices, one containing estimates of fuel consumption rates, the other total fuel consumption within each cell (the cells of the latter matrix contain the product of the cell values of the first two matrices).

The matrices can be used to answer a variety of questions. Some deal with the current status. For instance, how much fuel is consumed by commuter trips of less than one mile; which fraction of this fuel is consumed by cars exceeding a certain weight? How much fuel is consumed by travel in various speed ranges? Another kind of question asks what will happen in the future, if current trends continue? For instance, if the vehicle turnover follows the past trends, how will fuel consumption change with population changes or their regional distribution? A third kind of question is based on postulated changes. What will happen if the mix of future vehicle sales changes in a specified pattern? What would be the effect of banning Sunday driving, except to work? What would be the effect of changing the pattern of short commuter trips? What is the potential for fuel savings through changes in certain vehicle characteristics, such as the dependency of fuel consumption on average speed, or on trip length?

We conclude that from the NPTS data, VMT estimates can be obtained which are accurate to about 3 percent for aggregate figures. From vehicle counting data, aggregate VMT figures could be derived with about 3 percent accuracy, under ideal conditions. However, because of great differences between the extent of the various states' counting programs, the actually achievable accuracy will be lower. The statistical accuracy of estimates from odometer readings will depend strongly on how they are analyzed. However, they probably have an upward bias of as much as 5 percent.

These error estimates hold for the total VMT figures. Individual cell values, and even values in the cells of two-dimensional tabulations will have considerably lower accuracy.

Even these error estimates are not very precise. Better error estimates can be obtained only by a statistical analysis of the actual data, and a comparison of the results from different data sources.

Quantifying the Matrix

Figure 4 illustrates how the three proposed data sources can be used to estimate VMT for the cells of the matrix. In addition to the data from these sources, vehicle registration files, and driver license files can be used to improve the accuracy of the estimates.

There are two basic steps: (1) Estimate VMT figures as disaggregated as possible from each source, resulting in a "margin" of the comprehensive matrix. (A "margin" is a matrix using some, but not all factors.) (2) Combine these marginal matrices into the comprehensive matrix. In addition, various comparisons between VMT estimates can be made to assess their reliability.

The Nationwide Personal Transportation Study uses three independent bases of information: (1) Estimates of the annual VMT for each household vehicle, (2) Estimates of annual VMT for each licensed driver in the household, and (3) Detailed information on each--with the exception of joyrides returning to the point of origin--trip by household members. The latter is the most detailed source of travel information. VMT information, however, can not be very accurate, because it is based on the respondent's subjective estimates. The accuracy of VMT estimates per vehicle may vary between very good and highly questionable. Annual VMT per driver is probably the least accurate information. All three bases, however, are useful for checking the internal consistency of the data in NPTS, and for obtaining more reliable combined estimates.

Data from the continuous vehicle counting program will provide estimates of VMT disaggregated only by highway class and time. Additional information from classification counts is necessary to further disaggregate by vehicle type (and possibly class). The results of this first disaggregation will probably be less reliable because of the occasional nature of the classification counts. Estimates of VMT based on odometer readings are unique and important because they are the only ones based on actually measured mileage. These estimates, however, are probably biased upwards. Also, they allow disaggregation only by vehicle class and model year, but not by driving condition.

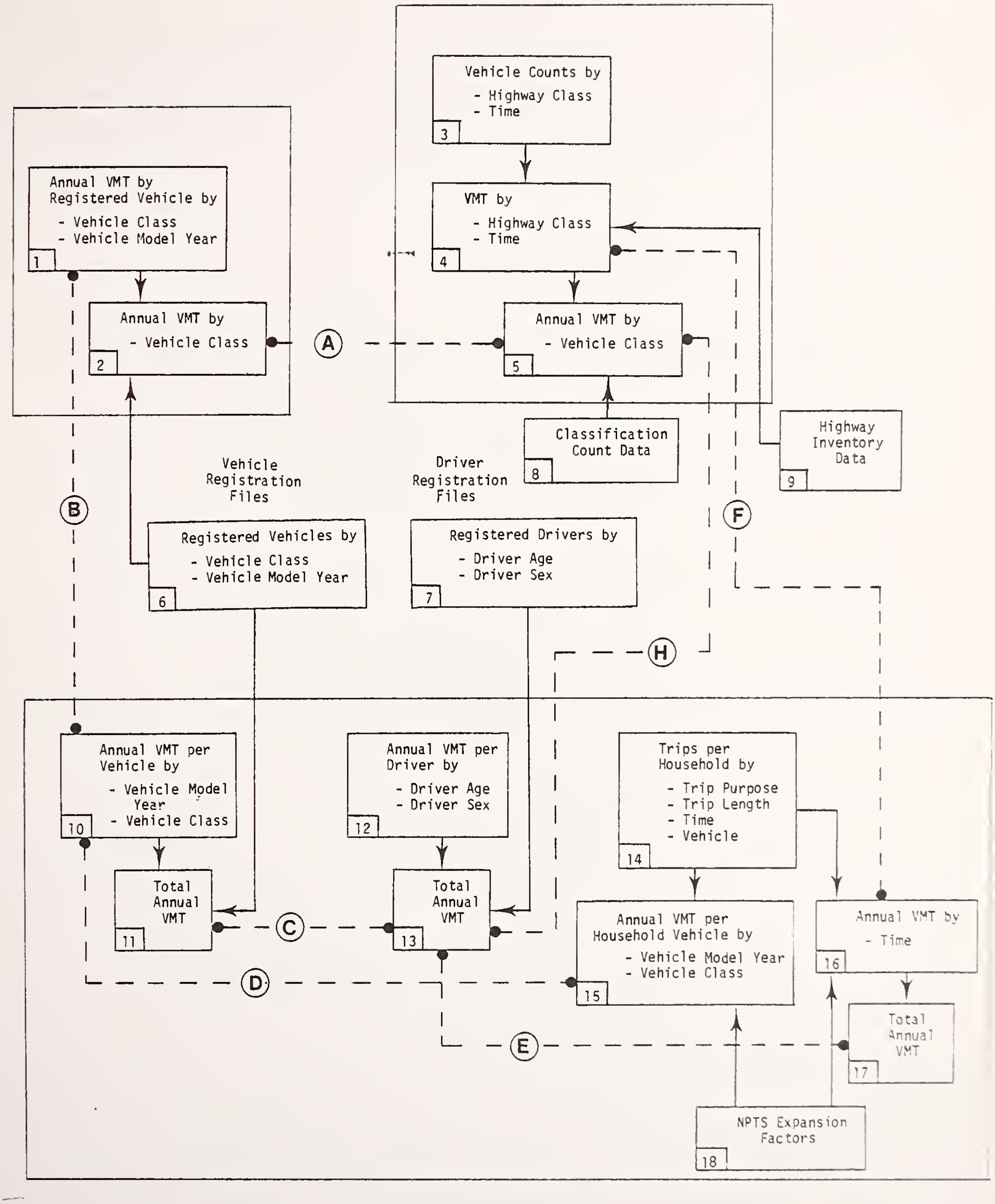
Vehicle Counts by
- Highway Class
- Time
3
Annual VMT by
Registered Vehicle by
- Vehicle Class
- Vehicle Model Year
1
VMT by
- Highway Class
- Time
4
Annual VMT by
- Vehicle Class
2
A
Annual VMT by
- Vehicle Class
5
Classification
Count Data
8
Highway
Inventory
Data
9
Vehicle
Registration
Files
Driver
Registration
Files
B
F
Registered Vehicles by
- Vehicle Class
- Vehicle Model Year
6
Registered Drivers by
- Driver Age
- Driver Sex
7
H
Annual VMT per
Vehicle by
- Vehicle Model
Year
- Vehicle Class
10
Annual VMT per
Driver by
- Driver Age
- Driver Sex
12
Trips per
Household by
- Trip Purpose
- Trip Length
- Time
- Vehicle
14
Total
Annual
VMT
11
C
Total
Annual
VMT
13
Annual VMT per
Household Vehicle by
- Vehicle Model Year
- Vehicle Class
15
Annual VMT by
- Time
16
D
Total
Annual
VMT
17
E
NPTS Expansion
Factors
18

Figure 4

In principle, such questions can be answered by selecting the affected cells of the matrix and calculating the resulting changes in fuel consumption. In practice, however, it is a major computational problem: even a "minimal" matrix which distinguishes only 3 to 6 values or categories for each factor has about 200,000 cells. A thorough analysis might allow one to reduce this to several 10,000 cells. Even this number is too large for manual manipulation, though the necessary calculations are very simple. For electronic computers this is a minor problem.

Therefore, a computer model has to be developed which allows storage of the detailed information of the matrix, and enables the user to:

- Access specified cells, and calculate aggregations of specified cells.
- Display selected two-dimensional matrices.
- Calculate the effects of changes in travel under specified conditions, or of fuel consumption per mile under specified conditions.

We estimate that a computerized model of the matrix could perform the necessary operations on the data to answer questions of the type illustrated for a computing cost (on a typical large-scale system) of less than $5.00.

1. INTRODUCTION

The objective of this study is to create a framework for describing automotive fuel consumption in terms of vehicle miles of travel under different driving conditions, fuel consumption per mile under these conditions, and total fuel consumed under these conditions, and for studying the effect of various changes upon fuel consumption. The scope is limited to vehicles for personal use: passenger cars and certain small trucks.

The specific objectives of Phase I, described in this report, are to:

(1) Categorize driving conditions into a multidimensional matrix which allows one to study potential fuel saving benefits of a variety of fuel economy measures,

(2) Assess information currently available with regard to its usefulness for filling this structure,

(3) Determine how currently available information can be better used, and which additional data are needed to fill the matrix, and

(4) Develop a plan for Phase II, to quantify the matrix.

The problem is approached in the following steps:

(1) Identify factors which influence fuel consumption, and organize them according to the relations between them.

(2) Select factors which suffice to classify driving conditions as dimensions for a multidimensional matrix.

(3) Identify existing sources of Vehicle Miles of Travel (VMT) information and assess their usefulness for quantifying the matrix.

(4) Identify other sources of data which may be used to derive VMT information needed to quantify the matrix.

(5) Determine how the matrix can actually be quantified using data from these sources.

(6) Describe how the information in the matrix can be used to study and answer questions on the effects of various trends in automobile usage and of various fuel saving policies.

The emphasis of the study is on driving conditions. Vehicle characteristics which are not of obvious importance to the user, or which do not interact strongly with driving conditions are not being considered. Also, individual driver behavior is not considered. However, average driver behavior, as it is influenced by driving conditions is implicitly incorporated in the empirical results.

The study is based on an extensive review of the literature, and on contacts with various agencies and organizations, primarily the Federal Highway Administration.

Appendix A is a bibliography, listing the literature reviewed. Appendix B presents briefly the findings of selected studies on the effects of various factors on fuel consumption. Its purpose is to give the reader an idea of the contents of these studies; no critical review was intended. Appendix C illustrates,using a very simplified example, how a comprehenxive matrix can be constructed from incomplete sources of information. Appendix D illustrates potential uses of the matrix with very simple examples.

2. CHARACTERIZING DRIVING CONDITIONS

2.1 Introduction

The objective of the first Task was to categorize driving conditions of personal vehicles into a multidimensional matrix which allows one to study potential fuel saving benefits of a variety of fuel economy measures.

We approached this problem in the following steps: 1) identifying those factors which influence fuel consumption and, therefore, have to be used to distinguish driving conditions; 2) finding relations between these factors and organizing them according to the relations; and 3) "collapsing" the comprehensive matrix including "all" factors so that redundancies are eliminated, but all factors relevant for selected fuel economy studies are included.

This three-step process was necessary for the following reason: "Factors influencing fuel consumption" are not unambiguously defined. *Grades,* for example, influence fuel consumption fairly directly, whereas *highway type,* (e.g., interstate, main rural road, secondary rural, etc.) has no direct influence, though it has a strong indirect influence. This is because highway type determines (in a statistical sense) *grades, curves, travel speed, frequency of stops,* etc., factors which have a more direct, well established influence. Information on travel by highway type may be more easily obtainable, and (for many purposes) more appropriate than information on VMT under combinations of grade, curvature, travel speed, stops per mile, etc. Similarly, *time of day* has no direct influence, but *traffic density* varies with time of day, and consequently the *average speed,* which has a well established influence on fuel consumption. Also, time of day, together with the *season* of the year and *geographical area* determine the expected *ambient temperature* which directly influences fuel consumption. Travel by time of day can be more easily estimated, and is also (from a traveler's point of view) more meaningful than travel by traffic density class or by temperature interval. Therefore, we use a very broad concept of "factors influencing fuel consumption" to provide a conceptual basis for a wide range of studies under different aspects. In Appendix B, we have listed information on "factors influencing fuel consumption" found in the literature which we reviewed as part of the first study task.

If all these factors were used to define a matrix--each factor corresponding to one dimension--the matrix would have many dimensions and a very large number of cells. Most VMT, however, would be concentrated in relatively few cells, because of the associations and causal relations between many of the factors used as dimensions of the matrix. The entries in cells with few VMT are likely to be relatively

much less reliable than those in cells with high VMT figures; most of the reliable information will be concentrated in relatively few cells. Also, in using the comprehensive matrix for numerical studies of the effects of fuel economy policies, one would have to pay special attention to vary the factors so that their empirical or causal relations are maintained.

Therefore, it is desirable to reduce the number of dimensions by selecting few, largely independent, important factors. There is, however, no natural unambiguous way to eliminate redundant factors. Factors which are important for one class of fuel economy programs, e.g., engine modification, are of little interest for other programs, e.g., highway design or transportation planning. Therefore, the selection of factors as dimensions of a matrix depends on the intended use of the matrix.

2.2 Identification of Factors

To identify factors influencing automotive fuel consumption, the literature listed in Appendix A was reviewed. Not all studies proved to be relevant; those papers from which information was used are cited. Appendix B presents brief summaries of the effects of the factors and relations between factors, as reported in the literature. No critical assessment of the validity of the finding was made, except in few cases. In addition to factors which are recognized in the literature, we identified factors which are related to others and which may be useful, either to complete the structure or to assist in the evaluation of special fuel economy programs.

We identified the following driving-condition-related factors:

Torque (Horsepower) and Engine Speed (RPM). These are the dimensions of the fuel consumption maps which are being developed for various engines at the Bartlesville Research Center [1], General Motors Research Labs [2] and elsewhere. This information combined with the time distribution of engine operation (in terms of torque and engine speed) is used in simulation programs to evaluate the effect of changes in operating factors like transmissions, gearing, etc. However, the torque and engine speed distribution is not a readily available item of travel information and secondly, there are important modifiers such as engine and drive train temperatures, which are determined by ambient temperature and trip history.

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[1] Marshall and Stamper, *Engine Performance Test of the 1975 GM 140-CID*
[2] Marks and Niepoth, *Car Design for Economy and Emissions*

Speed. Speed is the driving factor which empirically is most closely related to fuel consumption. However, one has to distinguish instantaneous (actual) speed and average speed over a distance (the attempted travel or design speed of a highway also plays a role). Instantaneous speed is directly proportional to RPM for a given gear ratio. Travel speed is influenced by the actual speed history, including acceleration, deceleration, and stops. Attempted or design speed, and traffic volume, influence average travel speed. Evans, Herman, *et al.* at GM have shown that average speed is the major determinant of fuel consumption rates in urban driving [3]. Numerous laboratory studies have shown that vehicles have a characteristic optimum fuel consumption rate relative to constant speed, maximum fuel economy falling generally between 40 and 55 mph [4]. However, most travel is not done at constant speeds, but rather over quite a range of speeds. Average speed, for example, or attempted or design speed is a more meaningful predictor of fuel consumption because it includes the changes in speed.

Acceleration/deceleration. Acceleration of the vehicle uses fuel because it requires increased torque; deceleration reduces the torque required. The number of stops per mile determines the need for deceleration and acceleration (though not necessarily their time pattern), as does the number and magnitude of slowdowns. Various factors determine the acceleration and deceleration pattern, primarily traffic conditions, such as stop and go traffic, and driving style. An aggressive, impatient style has more acceleration/deceleration than a more conservative driving style. There is some indication that an aggressive driving style can increase fuel consumption in suburban driving by as much as 15 percent [5].

Traffic volume. This influences fuel consumption indirectly because it influences the number of slowdowns and/or stops, and (together with attempted speed) the average travel speed. There is a considerable volume of traffic engineering literature (particularly the *Highway Capacity Manual* [6]) which relates traffic volume to average speeds on particular roadways (e.g. a two lane rural roadway with 1500 foot sighting distances for 80 percent of its length, or other similarly described situations).

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[3] Evans and Herman, "Multivariate Analysis of Traffic Factors Related to Fuel Consumption in Urban Driving"
[4] SAE Fuel Economy Measurement Procedures Task Force, *The Development of the New SAE Motor Vehicle Fuel Economy Measurement Procedures*
[5] Forrester, *et al. Gasoline Engine Economy -- A European Viewpoint*
[6] Highway Research Board, *Highway Capacity Manual* 1965

Highway surface characteristics, including ice or snow cover, influence friction and, therefore, the road load. The EPA reported that there can be a 15 percent mpg loss (at 50 mph cruising speed) from patched and broken asphalt [7]. The losses attributable to snow are similar. However, the degree of surface deterioration, or presence of a snow cover are not very practical factors for classifying driving conditions.

Grades influence fuel consumption because of the work needed to lift the vehicle. Part of this is recovered when moving downgrade. Since, on the average, the same number of vehicles travel in both directions, only the difference between uphill and downhill fuel consumption should play a role in aggregate fuel consumption. It is possible, however, that an interaction between temperature and grade (traffic in one direction during the morning rush hour, in the other direction during the evening rush hour) may cause a more complicated effect. Another potential effect of grades is related to speed, since speeds going upgrade and downgrade are likely to differ, and wind resistance is proportional to the third power of the speed. The effects of grades on fuel consumption can be substantial; the EPA reports that a 3 percent grade decreases mpg by 32 percent at 50 mph [7]. One problem with this figure is that cars tend to slow down on grades as drivers seem to limit continuous demand on the engine to 65-70 percent of maximum available power [8].

Curvature of the road influences fuel consumption in two ways: first, speed may be reduced and afterwards increased; and, second, energy is needed to change the direction of motion. Empirical studies have related observed speed on curves to their curvature and sighting distance. Claffey reports an increase in fuel consumption by 40 percent in traversing 12° curves at 50 mph [9], Claffey shows in a National Cooperative Highway Research Program study how changes in roadway geometry (grades and curves) can be justified from an energy conservation point of view [10].

Geographical area influences a wide range of characteristics: ambient temperature, wind and air pressure, and via the terrain characteristics, grades and curves. By means of population density, it influences trip length. Highway

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[7] EPA, *Factors Affecting Automotive Fuel Economy*
[8] Planning Environment International, *Vehicle Operation, Fuel Consumption, and Emissions as Related to Highway Design and Operation*
[9] Claffey, *Passenger Car Fuel Conservation*
[10] Claffey, *Running Costs of Motor Vehicles as Affected by Road Design and Traffic*

system mix and density are also related to geographic area by population and regional economic characteristics. There are certainly distinct rural/urban differences in traffic characteristics between various metropolitan areas [12] and differences in driving style between areas of the country [4]. Also, one finds more compact cars in the Northeast and on the West Coast than in the rest of the country.*

Air pressure, is on the average, related to elevation above sea level, influences fuel consumption via the air/fuel ratio. Claffey reports that the effect becomes substantial between 3000 and 4000 feet (about a 20 percent penalty) [10]. However, vehicles marketed in the mountains are usually specially equipped by auto manufacturers so that they do not suffer the power losses that would be suffered by a car with a regular carburetor.

Wind influences fuel consumption by increasing or decreasing road load. The effects of head and tail winds cancel each other out, on the average. The smaller effects of cross winds (or the cross component of wind) do not cancel each other. Obviously, the wind characteristics are related to geographic area. The EPA reports that an 18 mph crosswind causes a 2 percent mpg loss at 50 mph [7].

Time, in the general sense of time of day, day of week, and week (or month) of the year, indirectly influences fuel consumption in many ways. It influences ambient temperature and wind, and is related to trip purpose and (thereby) to traffic volume and trip length. The Nationwide Personal Transportation Survey conducted in 1969-1970 shows the marked relations between trip times and trip purposes [13]. Obviously, most work-related personal trips were concentrated in the hours between 7-9 AM and 4-6 PM. The distribution of trips for other purposes such as personal business or recreation is also highly specific. Beyond the daily or weekly pattern, there are changes in tripmaking which are seasonal. Ambient temperature varies in a daily and a seasonal pattern, being influenced also by the geographical area.

Temperature plays different roles in fuel consumption. Fuel temperature requires only a scaling factor, because the volume of a given mass of fuel (on which its energy content depends) varies with temperature. In addition, it may influence the combustion process. The temperature of the engine, transmission,

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*CEM analysis of R. L. Polk data published in *Ward's Automotive Yearbook* [11]

[12] Chang and Herman, *An Attempt to Characterize Traffic in Metropolitan Areas*

[13] U.S. DOT, *Nationwide Personal Transportation Study*

differentials and bearings influence the viscosity of the lubricants and, thereby, the energy required to overcome friction. Ambient temperature influences temperature of fuel and lubricants. Scheffler and Niepoth show that there is a large initial fuel economy penalty, which is present even after the vehicle is fully warmed up. On a 10°F day, fuel economy for the first mile of travel is approximately 30 percent of fully warmed up fuel economy [14].

Trip length has a strong influence on fuel consumption because the temperature of the engine, transmission, etc. depends on trip length.(together with the recent operating history of the engine). In the 1969-1970 NPTS, the average trip length was reported as 8.9 miles. However, other comparable studies have found average trip lengths of 7.5 [15], 6.4 [16] and for weekday trips, 3.55 [17] miles. A trip has to be at least 20 miles long to fully warm up the engine. However, the greatest number of trips are short trips, where the engine and drive train hardly have time to reach fully warmed up fuel economy.

Table 2.2-1 illustrates the magnitudes of the effects of various factors on the fuel consumption rate (gallons per mile). These estimates are based on various sources, primarily [10]:

TABLE 2.2-1

MAGNITUDE OF THE EFFECT SELECTED FACTORS HAVE ON FUEL CONSUMPTION

Factor	Range of Factor	Fuel Consumption Effect*
Uniform Speed	10 mph to 70 mph	2.0
Slowdown	One 10 mph slowdown per mile	1.1
Stops	One stop per mile	1.3
Trip Length	1/2 mile up to infinity	4.0
Grade	0 to 10%	4.0
Curvature	0 to 12°	2.0
Highway Surface	Patched asphalt to loose gravel	1.5 to 2.0
Ice/Snow Cover		1.1
Elevation	Up to 4000 feet	1.25
Temperature	0 to 100° F	2.0

*For a continuous factor, the "effect" is the ratio between the highest and the lowest fuel consumption rate in the given range. For "slowdowns" and "stops" the effect is the increase of the fuel consumption rate by one such act per mile. Ice/snow cover increases fuel consumption by approximately 10 percent.

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[14] Scheffler and Niepoth, *Customer Fuel Economy Estimated from Engineering Tests*

[15] Kearin, *et al., A Survey of Average Driving Patterns in Six Urban Areas of the United States*

[16] Johnson, *et al., Measurement of Motor Vehicle Operation Pertinent to Fuel Economy*

[17] McMillan and Assael, *National Survey of Transportation Attitudes and Behavior*

2.3 The Relations Between the Factors

As discussed in Section 2.2., many driving condition factors are causally or empirically related to the rate of fuel consumption. Figure 2.3-1 shows the relations found in the literature, with some minor omissions. Some of the factors directly influence fuel consumption per mile; other factors indirectly influence fuel consumption per mile, by influencing intermediate factors. The relations shown are not always well quantified. Also, typically, the dependence of fuel consumption on only one (or occasionally two) factor(s) was studied. In reality, more complex interactions between several factors are likely to occur.

Even the "direct" relations shown in Figure 2.3-1 are not always direct in a causal sense. Average trip speed, for instance, is related to fuel consumption because both are influenced by actual travel speeds, frequency of stops, frequency and degree of slowdowns, etc. Trip length, on the other hand, influences fuel consumption because it influences the engine and drive train temperatures, and the type of highway used, thereby influencing speed, acceleration and deceleration patterns. Figure 2.3-2 rearranges the factors influencing fuel consumption so that direct causal relations are shown, even though they may currently not be quantified. The main features of this Figure are: (a) the focus is on the time distribution of torque and engine speed, which (together with the fuel consumption map)* determines fuel consumption; (b) the torque x engine speed time distribution is determined by the speed x acceleration time distribution, together with road load (resulting from the factors in "box" I) and transmission characteristics; (c) average speed is no longer an intermediate factor to predict fuel consumption but is rather determined by many of the same factors.

From these Figures, one can see that fuel consumption per miles traveled can be estimated, with varying reliability, from relatively few factors. A combination of trip purpose, geographical area, and vehicle characteristics (at least weight) will allow some estimate of the fuel consumption, though it will not be very precise. This is because the relations between trip purpose and geographical area, and the variables more directly influencing fuel consumption are quite weak. On the other hand, a combination of time, highway type, ADT, trip length and vehicle characteristics will allow a much better prediction of the fuel consumption because these variables are causally more closely related to it. There are many

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*A fuel consumption map shows curves of equal fuel consumption in a torque x engine speed diagram. It is engine specific.

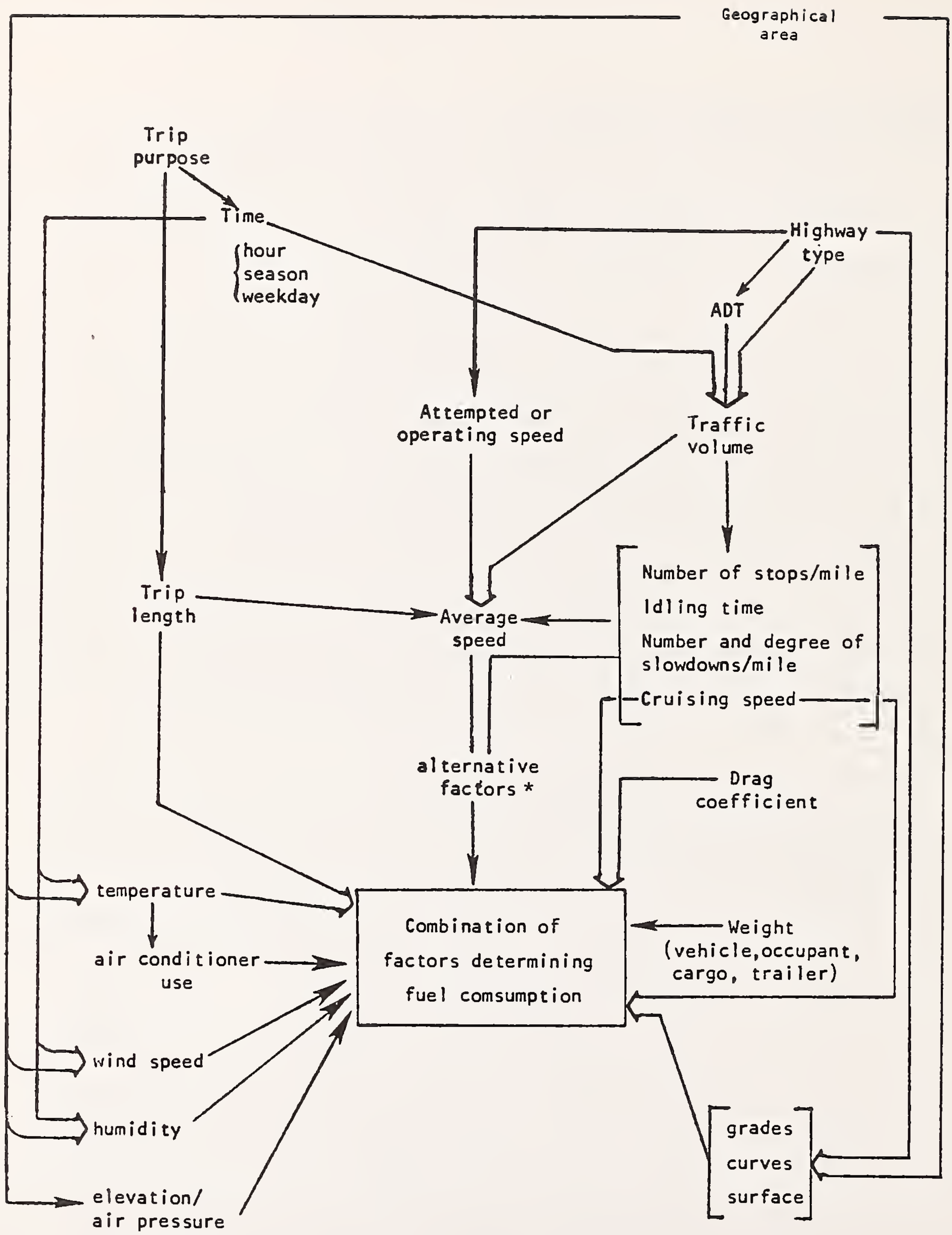

Figure 2.3-1. Driving Conditions Influencing Fuel Consumption, as Found in the Literature.

Lines indicate causal or empirical relations. Arrowheads show the direction of influences; if several lines enter an arrowhead, the corresponding factors interact.

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*Average trip speed, or a combination of cruising speed, number of stops per mile, etc. are alternative factors, largely describing the same influences.

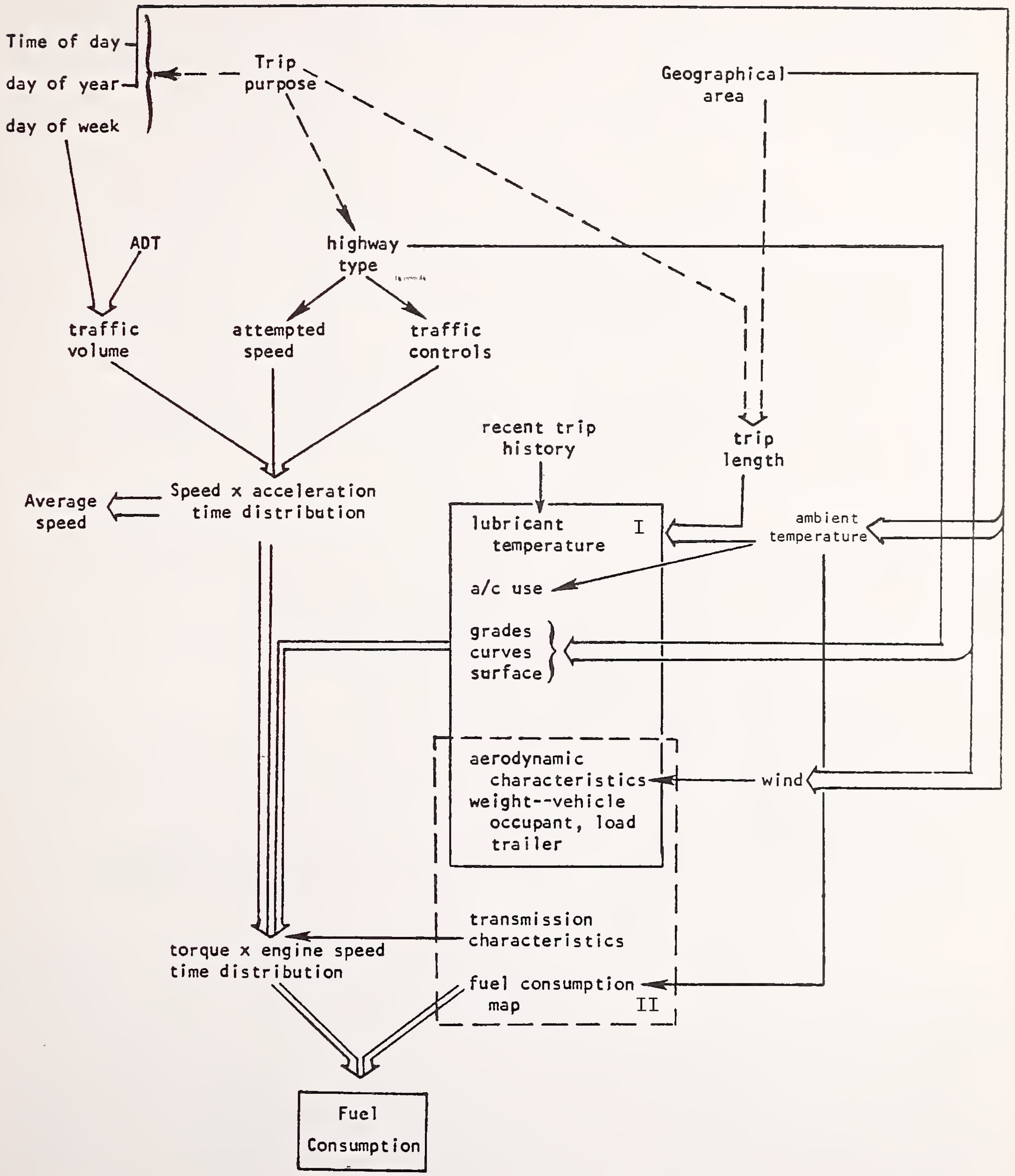

Figure 2.3-2. The Influence of Driving Conditions on Fuel Consumption Organized According to Causal Relations.

Solid arrows indicate physical or other strong relations, broken lines weaker relations. Several lines with a common arrowhead indicate interactions of factors. "Box" I comprises factors which, together with acceleration, determine engine load; "box" II encompasses vehicle factors, as distinct from driving conditions.

ways to select more or less independent factors which allow an estimate of the fuel consumption rate under the corresponding driving conditions. The choice is not simply one between better and less good estimates; it also involves the importance of the selected factors with regard to the specific aspects of the problem studied.

Figure 2.3-3 presents an example of how a network of causal relations can be used to estimate fuel consumption rates as a function of relatively few factors. It describes a process developed by Claffey [10] to estimate fuel consumption rates by state (51), highway type (6) and vehicle type (4). From various sources he estimates, for any combination of these three factors, the values of other factors, such as speed, grades, curves, stops per mile, ambient temperature, etc. For the influence of these factors, he obtained empirical relations. Combining these two steps, he obtained fuel consumption rates for all combinations of the basic factors.

2.4 Factors and Matrices

Each factor influencing fuel consumption can be used to define a dimension of a multidimensional matrix. For each factor, at least two levels have to be distinguished. The combinations of certain levels for each factor describe the cells of the matrix, as illustrated in Figure 2.4-1.

To deal with the problem of this study, each cell of the matrix has to "contain" two numbers, or one needs two "parallel" matrices: (1) the fuel consumption rate (gallons/mile) when driving under the conditions described by the combination of factor levels defining the cell; and (2) the total number of miles driven under these conditions. Total fuel consumed under these conditions is the product of these two numbers.

Two factors determine the number of cells of the matrix: (1) the number of levels of each factor; and (2) the number of factors. Most factors are continuous; therefore, definitions of levels are arbitrary. If one distinguishes many levels, driving conditions between adjacent cells differ little; however, the problem of collecting VMT data becomes more extensive. If one distinguishes only a few levels, the collection of VMT data may be made easier, but driving conditions may not only differ between cells, they may vary considerably within each cell, and estimates of fuel consumed under the conditions of the cell may become unreliable. The number of cells increases rapidly with the number of factors and levels, as shown in Table 2.4-1. Therefore, a careful selection

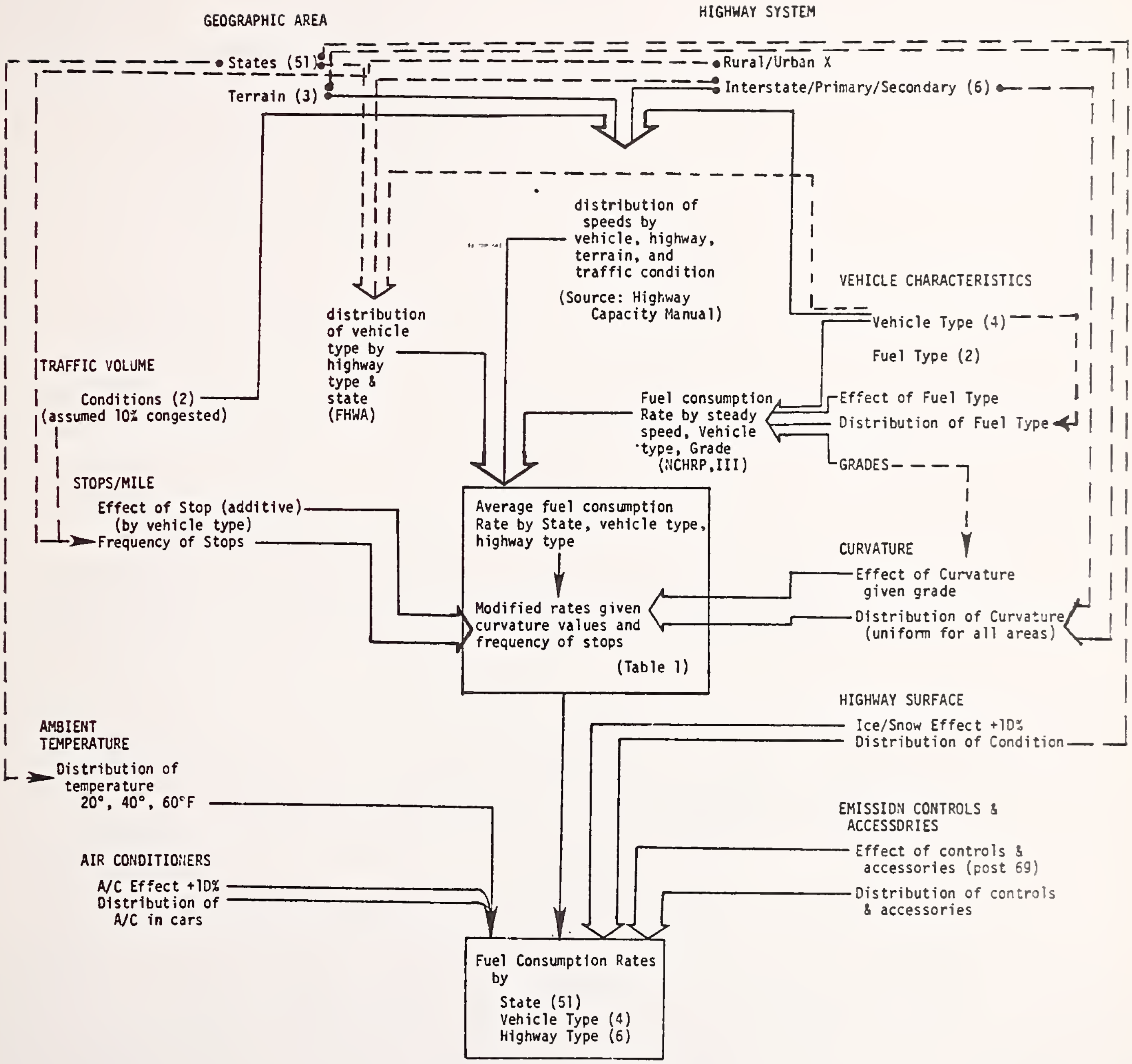

Figure 2.3-3. Procedure to Estimate Fuel Consumption per VMT, Presented as a Network.

Broken arrows indicate estimates of intermediate factors from the three basic factors--state, vehicle type, highway class--solid arrows show empirical relations between the intermediate factors and the fuel consumption rate. Claffey [10].

of factors and choice of levels is necessary to define a matrix which is practically usable.

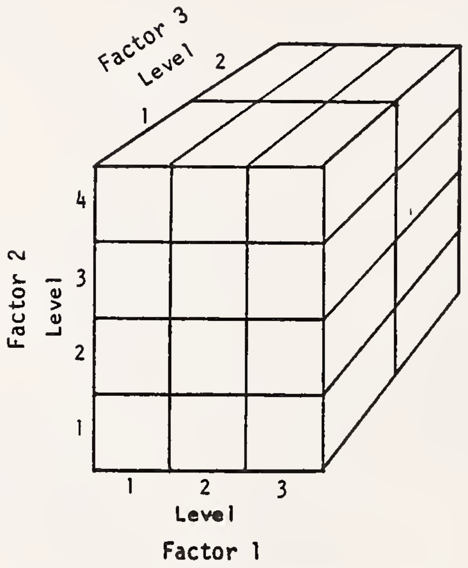

Figure 2.4-1. Illustration of a Matrix Defined by Three Factors.

Factor 1, assumed to have 3 levels; Factor 2 with 4 levels; and Factor 3 with 2 levels, resulting in a 3-dimensional matrix with 24 cells.

TABLE 2.4-1

NUMBER OF CELLS IN A MATRIX WITH ONE DIMENSION FOR EACH FACTOR, ASSUMING THE SAME NUMBER OF LEVELS FOR ALL FACTORS
(K = thousands)
(M = millions)

No. of Levels	Number of Factors 2	4	6	8	10	15	20
2	4	16	64	256	1024	33K	1M
3	9	81	727	6561	59K	14M	3KM
4	16	256	4096	66K	1M	1KM	1MM
5	25	625	16K	391K	10M	31KM	95MM
6	36	1296	47K	1680K	60M	5MM	4KMM

A two-dimensional matrix can easily be presented on paper. This allows visual screening and recognition of patterns and special features, as well as simple calculations using the numbers of a matrix. Three- and four-dimensional matrices can still be represented in a meaningful way on paper by presenting a sequence of two-dimensional matrices or "nesting" them. However, certain patterns and features can easily be overlooked. Alternative presentations of

the same matrix can reduce this risk, but not eliminate it completely. Beyond four dimensions, a presentation on paper is of limited usefulness. It is more promising to store the information in a computer and display many alternative aspects--specific cells, submatrices, marginal matrices--as needed, as well as using the computer to perform calculations with the stored data.

However, even if the matrix is stored in a computer, the figures in Table 2.4-1 show that it is necessary to limit the number of factors and levels, in addition to the problem of collecting meaningful data for a large number of cells.

2.5 Examples of Alternative Matrices

In an attempt to reduce the number of dimensions in the matrix, we considered the needs of different users: automotive engine designers, highway planners/engineers, travel data collectors, and transportation system planners. The following are illustrations of matrices for different users, based on our perception of their needs.

Automotive Engine Designers. The most detailed description of fuel consumption by a vehicle is given by the "fuel consumption map" which shows contour lines of equal fuel consumption in an engine-speed/torque coordinate system. This fuel consumption information, combined with the time a vehicle spends in the different parts of the engine-speed/torque diagram determines total fuel consumption over a trip, a driving cycle, or an aggregation of trips. For given driving cycles, such as the SAE or EPA cycles, designers can optimize engines to minimize total fuel consumption.

Directly corresponding to the torque/engine speed coordinates are acceleration and speed, given the transmission characteristics and the total engine load. Therefore, speed/acceleration distribution compares to the torque/engine speed distribution. Total engine load is determined by car weight, aerodynamic drag, grade, curvature, highway surface, and the temperature of the engine, transmission and differential lubricants. For these temperatures, trip length and ambient temperature appear to be adequate proxy measures. Figure 2.5-1 presents the factors listed in descending order of importance; only factors varying with the operation of the vehicle are listed. Design factors, such as transmission characteristics, vehicle weight, tire characteristics, etc. are omitted because they are fixed for a given vehicle.

First Level of Factors	More Detailed Factors
• Speed	
• Acceleration	
• Load	- Grade load - Curvature load - Aerodynamic (speed dependent)
• Vehicle temperature	- Ambient temperature - Trip length

Figure 2.5-1. Dimensions for the Engine-Oriented Matrix.

Highway Planning. Of interest are those factors which can be modified by highway design or traffic control, and those which strongly interact with them. The physical characteristics of the highway in the network of factors are grades, curvatures, and highway surface. Operating speed (as defined in the *Highway Capacity Manual*) is essentially the design speed of the highway. It, together with traffic volume, determines average travel speed by influencing the number of stops and slowdowns.

A tentative list of dimensions for the highway-oriented matrix is presented in Figure 2.5-2.

First Level of Factors	More Detailed Factors
• Operating Speed	
• Traffic Volume	
• Variation of Speed	- Number of Stops/Mile - Number of Slowdowns/Mile
• Grade	
• Curvature	
• Surface	

Figure 2.5-2. Dimensions of a Highway-Oriented Matrix.

Data Collection oriented matrices are those where the emphasis is on ease of collecting reliable data. There are two basically different ways of collecting detailed VMT data: by sampling highway segments, and by sampling vehicles. There are several ways of sampling vehicles: by interviewing drivers at a great level of detail, as in the NPTS;* by instrumenting a sample of vehicles;

*NPTS: Nationwide Personal Transportation Study sponsored by the Federal Highway Administration in 1969-70 and in 1977.

and by "chasing" the sampled vehicles. The latter two methods can give essentially the same data. Figures 2.5-3 and 2.5-4 show the matrices which can be quantified with information from these two approaches.

- Geographical area
- Highway class
- Traffic volume
- Cruising speed distribution
- Time of day
- Day of year
- Day of week
- Ambient temperature
- Surface conditions
- Gross vehicle type

Figure 2.5-3. Dimensions of Data Collection-Oriented Matrix, Obtainable from Highway Sampling.

- Geographical area
- Highway class
- Time of day
- Day of year
- Day of week
- Average speed (approximate)
- Use of air conditioner
- Trip length
- Ambient temperature
- Precise vehicle type

Figure 2.5-4. Dimensions of Data Collection-Oriented Matrix, Obtainable from Vehicle Sampling.

Transportation Planning-oriented matrices use factors which are related to the purpose of travel, and actually and potentially available alternative modes of travel. Figure 2.5-5 lists the dimensions of such a matrix.

- Trip purpose
- Time of day
- Day of week
- Season of year
- Trip length
- Availability of public transportation
- Traffic volume
- Highway Class
- Geographical area

Figure 2.5-5. Dimensions of a Transportation-Oriented Matrix.

2.6 The Matrix Selected

From the various possible alternatives, factors relating to transportation planning, and key vehicle characteristics were selected, namely:

- Trip purpose
- Trip length
- Time
  - Time of day
  - Day of week
  - Week, month or season of year
- Highway class
- Geographic area
- Vehicle weight
- Vehicle age (model year).

Figure 2.6-1 shows how these factors are, on the basis of existing information, related to each other and to intermediate factors which determine the fuel consumption rate. The factors are not completely independent: there are associations between trip purpose and the time a trip is made, between trip purpose and trip length, and also between geographical area and trip length. Also (not shown), it is probable that there are relations between trip length and highway class, between trip purpose and vehicle characteristics, and possibly others. Such relations will lead to a concentration of VMT in certain cells of the matrix. However, we expect that the concentration will be strong in only one case:

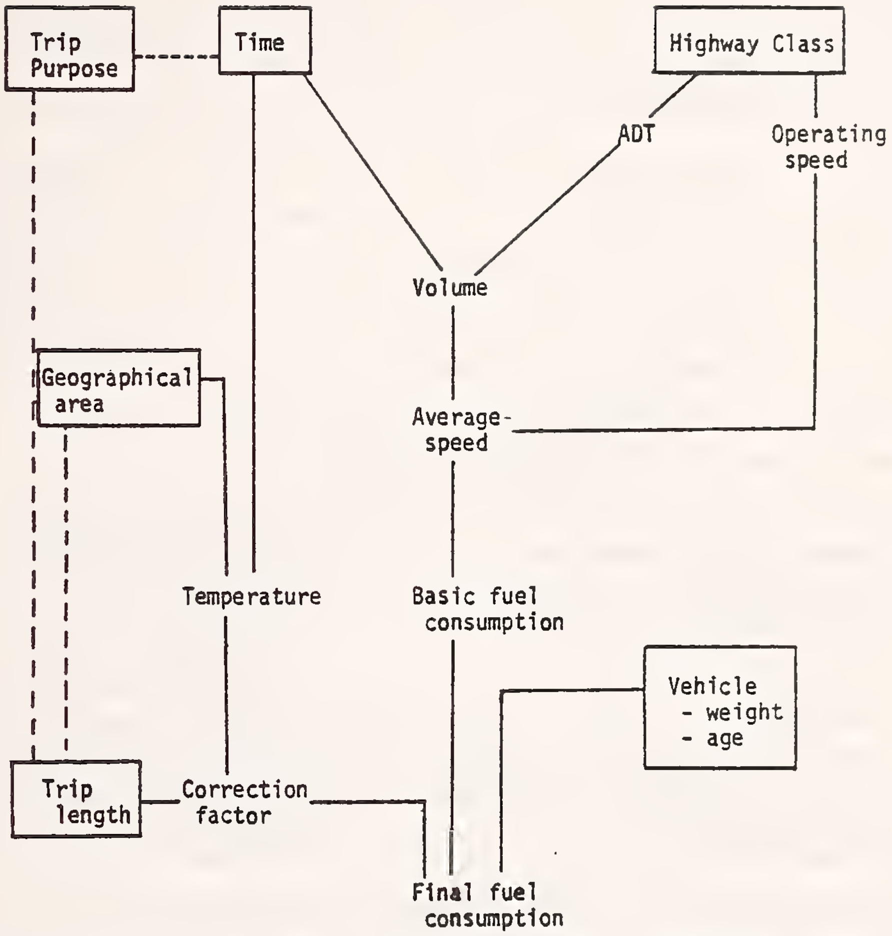

Figure 2.6-1. Relations between the Selected Factors and Fuel Consumption.

In "boxes" are the factors used as dimensions for the matrix, which influence fuel consumption indirectly via the other factors. Broken lines indicate associations, or weak causal relations.

home-to-work trips, which are concentrated during the commuter hours on workdays and rare at other times. The selected factors influence the fuel consumption rate in three ways: (1) time and highway class determine the average speed (perhaps also influenced by geographical area); (2) time and geographical area determine the average ambient temperature which (together with the trip length) determines the relative fuel efficiency of the vehicle; (3) the basic fuel consumption of the vehicle is primarily determined by weight and model year (which at any given time corresponds to the vehicle age). These three factors determiie the estimated fuel consumption rate.

The second step in defining the matrix is to select levels for the factors. In order to keep the number of cells low, a small number of levels for each factor is desirable. On the other hand, a small number of levels can result in grouping driving under quite different conditions into each cell. This makes the matrix less informative and also reduces the sensitivity of analyses based on the matrix. To some extent, these effects can be reduced by carefully defining the levels for each factor. In the following paragraph, we are suggesting classifications which, for given numbers of levels, keep the differences in driving conditions within each level relatively small, and between the levels relatively large. The suggestions are based on our review of the literature.

Trip Purpose. The most detailed classification available is used in the 1977 Nationwide Personal Transportation Study:

1. To place of work
2. Work-related business
3. Convention
4. Civic/Education/Religious
5. Eat meal
6. Doctor or dentist
7. Shopping
8. Family or personal business
9. Visit friends or relatives
10. Pleasure driving
11. Sightseeing
12. Entertainment
13. Recreation (participant)
14. Vacation
15. Change of vehicle without change of mode
16. Change means of transportation
17. Pick up or leave off passengers
18. Return home
19. Lodging (overnight)
20. Social
21. Other.

A minimal categorization is used in some modeling work:

1. Home-based work trips
2. Non-home-based work trips
3. Non-work trips.

A more realistic intermediate classification is:

1. Work trips: Home to work, or other work or business
2. Necessary personal activity trips: Shopping, medical or dental
3. Civic, educational, religious
4. Social and recreational trips.

Trip Length. The most detailed categorization is obtainable from NPTS: <1/2 mile, 1/2 - 1 mile, 1, 2, ..., n miles. The minimum categorization would be related to what seems to be break points in trip characteristics:*

1. 1/2 to 3 mile trips are on local streets.
2. 3 to 10 mile trips, of which part is on some higher level feeder/collector roads.
3. 11 and more mile trips generally using arterial highways, after reaching them on low order roads.

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*See Figure 3.4.2-1

A finer classification is desirable for two reasons: (1) the fuel consumption rate depends strongly on trip length for short trips (up to about 10 miles); and (2) it is worthwhile to know what the effects are of replacing very short automobile trips by walking, bicycling, or use of public transportation, where applicable. The following classification appears to be as fine as desirable:

1. <1/2 mile
2. 1/2 to 1 mile
3. 1 to 2 miles
4. 3 to 4 miles
5. 4 to 6 miles
6. 6 to 10 miles
7. 10 or more miles.

Time

Time of Day. The most detailed information available is hour of the day. The minimum realistic categorization would be: nighttime, rush hours, and non-rush hour daytime. However, morning and evening rush hours differ in terms of traffic volume as well as mix. Therefore, a more realistic categorization is:

1. Evening: 1800 - 2100 hours
2. Nighttime: 2100 - 0700 hours
3. Morning Rush Hours: 0700 - 0900 hours
4. Daytime: 0900 - 1600 hours
5. Evening Rush Hours: 1600 - 1800 hours.

Classes 1 and 2 can probably be combined with little loss of discrimination.

Day of Week. The finest breakdown is by day of week. The minimum is weekday, weekend. However, because of some difference between Saturday and Sunday, the following categorization is preferable:

1. Weekday
2. Saturday
3. Sunday.

Week, Month or Season of Year. Traffic volume and thereby speed, and ambient temperature vary through the year. Distinguishing the 12 months appears a reasonable compromise between distinguishing 52 weeks and the minimum of distinguishing only four seasons. The latter, or 6 periods of two months, may, however, be sufficient.

Highway Class. The most important effect of highway class is that it determines average travel speed. A minimal classification is:

1. Interstate highways
2. Other urban highways
3. Other rural highways.

It is based on average fuel consumption for six classes of highways, as determined by Claffey. The most detailed classification is the 14 FHWA highway

categories, which, however, include administrative considerations that have no relation to travel conditions. A more practical classification, based on average travel speeds as given by Johnson [16], is the following:

	Road	mph
1.	Expressway	50-55
2.	Expressway-Business Route, Rural Highway	40-50
3.	Suburban Artery	25-30
4.	Urban Artery Strip Commercial Suburban Street	20-25
5.	Central Business District Urban Street	17

Another classification, considering the function of the highway, has been developed by the Federal Highway Administration [18], namely:

1. Interstate
2. Other Freeway/Expressway
3. Other Principal Arterial
4. Minor Arterial
5. Major Collector
6. Minor Collector
7. Local.

However, an urban/rural distinction would have to be added to this to account for differences in travel speeds.

Geographic Area. The most detailed practical classification would be the 50 states (combining the District of Columbia, e.g., with Maryland). The least would be North, South. If one wants to aggregate into fewer areas, the criteria for aggregation becomes important. Population density, economic characteristics, terrain are such criteria. We believe that the influence of such factors is accounted for--to a large extent--by vehicle miles of travel, travel speed, and highway characteristics. The regional aspect which is not accounted for by these factors is climate, which influences seasonal as well as daily temperature variations. The following is a classification for the 48 contiguous states, based on climatic zones [19].

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[16] Johnson, R. M. *et al. Measurement of Motor Vehicle Operation Pertinent to Fuel Economy.*
[18] Cornean, "National Functional System Mileage and Travel Summary"
[19] S. B. Cohen, *Oxford World Atlas*

	Code	States
1.	21^1	CA
2.	21^2	OR, WA
3.	22^3	ID, ME, NH
4.	31	AL, AR, DC, DE, GA, FL, LA, MD, MI, MS, NC. OK, SC, TN, TX, VA
5.	32^2	KY, WV, WY
6.	32^3	CT, CO, IA, IL, IN, KS, MA, MN, MO, MT, NB, ND, NJ, NY, OH, PA, RI, SD, VT, WI
7.	x	AZ, NM, NV, UT

Explanation of code:

First digit: summer temperature	2: 10° - 20°C 3: > 20°C
Second digit: winter temperature	0: > 13°C 1: 2 - 13°C 2: < 2°C
Third digit (superscript) Seasonal temperature range	1: < 12°C 2: 12°C - 24°C 3: 24°C - 36°C

x = arid climate.

A slightly more aggregate classification which also avoids grouping distant states together is the following:

1. Northeast: WI, IL, IN, MI, OH, KY, WV, PA, MD, DE, NJ, NY, VT, NH, ME, MA, CT, RI
2. Northcentral: MT, WY, CO, ND, SD, NB, KA, MN, IA, MO
3. South: OK, TX, AR, LA, TN, MI, AL, VA, NC, SC, GA, FL.
4. Northwest: WA, OR, ID
5. Southwest: CA, NV, UT, AZ, NM.

Vehicle Weight. All studies show that vehicle weight has a very strong influence on fuel consumption. The EPA uses inertia weight classes of 250 and of 500 pounds to categorize vehicles for testing. Classes of 500 pounds width are so wide that weight variation within that range has a noticeable effect. However, to use narrower classes is probably impractical, because already

eight 500 pound classes are needed to cover the weight range of passenger cars, and another nine classes are needed to cover the weight range for light trucks. A more practical approach is to group passenger cars into classes, such as subcompacts, compacts, intermediate, and full size/large cars, and assign to each class its sales-weighted average weight. The situation for trucks is slightly more complicated, because trucks with a gross vehicle weight (GVW) up to 10,000 lb will be considered, if used for personal transportation. Actually, trucks with 10,000 lb GVW have a shipping weight of about 5000 lb and trucks with a 6000 GVW have a shipping weight of about 3000 lb. If trucks are used for personal transportation, the total weight is likely to be closer to the shipping weight than to the GVW. Again, it appears reasonable to distinguish only two or at most three classes of light trucks, and to calculate average shipping weight for these classes.

Weight is not the only vehicle factor influencing fuel consumption. At higher speeds, the aerodynamic drag, which depends on the vehicle shape, becomes important, but for most driving conditions it is negligible. For most conditions, idle fuel flow rate is an important factor [20], and a more refined vehicle classification may use this factor.

Vehicle Age. Vehicle age in itself has only an indirect influence on fuel consumption, because older vehicles are more likely to be defective or not properly tuned. However, in any given calendar year, it corresponds to the model year of the vehicle, and there are many differences between cars of different model years. Until recently, there has been a continuous decline of the average fuel economy of U.S. cars over the model years [21]. However, most of this decline is due to changes in vehicle weight, and not to changes in fuel economy within each inertia weight class. From 1957 through 1967, there was no trend apparent within the classes. Recently, however, there have been major changes. A look at fuel economy trends adjusted for model mix [22] suggests distinguishing pre-1968 model years, 1968 through 1971, 1972 through 1974, and from 1975 on, each model year. This would result in six categories for travel in the 1977 calendar year, increasing by one for every following calendar year. To reduce

[20] Evans and Herman, "A Simplified Approach for Calculations of Fuel Consumption in Urban Traffic Systems."

[21] Austin and Hellman, "Passenger Car Fuel Economy, Trends and Influencing Factors."

[22] Austin *et al.*, "Passenger Car Fuel Economy Trends through 1976."

the number of levels, the 1968 through 1974 model years may be combined into one class; in future calendar years it will also be possible to combine all pre-1975 model years into one category.

If one used the finest level of detail discussed for all factors, the resulting matrix would have 60 million cells! If one used the lowest level of detail, it would have nearly 40,000 cells; because of the lack of detail, however, its usefulness would be limited. We believe that the following numbers of levels for the factors are a reasonable compromise:

Trip Purpose:	4
Trip Length:	7
Time of Day:	4
Weekday:	3
Season:	4
Highway Type:	5
Area:	5
Vehicle Class:	6
Vehicle Year:	5

This would result in a matrix with 1,008,000 cells. Such a matrix could be handled using modern computers, but it would be expensive. However, it is unlikely that it will be possible to obtain meaningful data for all these cells. Preempting the findings of later phases of the study, we recognize two prime sources of vehicle miles of travel information: the Nationwide Personal Transportation Study, and the continuous vehicle counting program. The first provides, in principle, data for an 8-dimensional matrix (I in Figure 2.6-2), the second for a 5-dimensional matrix (II). They can be combined to the desired 9-dimensional matrix. However, when combining the matrices, one implicitly assumes that highway class is independent of trip purpose, trip length, vehicle age, and vehicle weight. This is probably not completely correct, but the available data provide no better information. Because of the implicit assumption of independence, the resulting 9-dimensional matrix contains no more information than the 8- and 5-dimensional matrices from which it is generated. They have 201,600 and 1,200 cells, respectively. Thus, only 202,800 data need to be stored. In addition, it is likely that an analysis of the NPTS data will not allow estimation of all interactions within the 8-dimensional matrix. This will reduce considerably the number of cells actually needed, replacing the one 8-dimensional matrix with several matrices of lower dimensions.

Overall, we conclude that a matrix with the selected factors as dimensions, distinguishing meaningful levels for each factor, will be large in terms of the

number of cells, but the information needed can be stored in a more compact manner which can easily be handled by today's electronic computers.

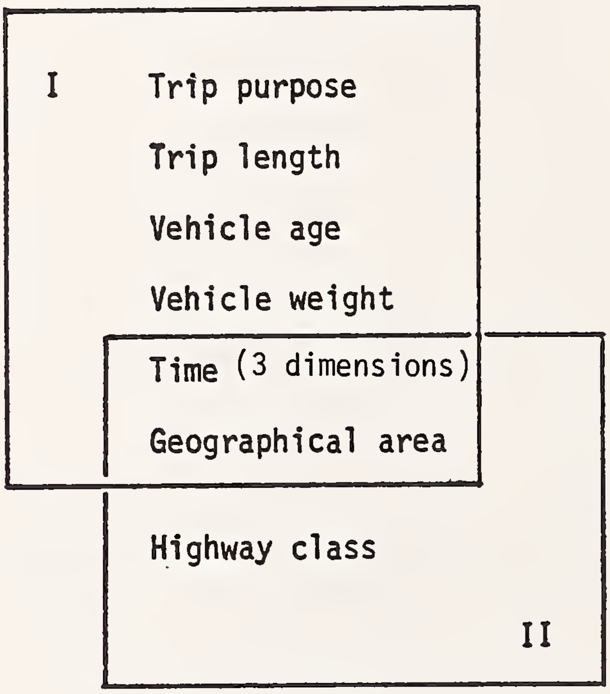

Figure 2.6-2. Illustration of How Two Matrices based on Available Data can be Combined to a Comprehensive Matrix.

Combination of one 8-dimensional (I) with one 5-dimensional (II) matrix, with four common dimensions. Matrix I can be developed from NPTS data, Matrix II from data from the continuous vehicle counting program. To make this combination, certain assumptions on independence have to be made.

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3. SOURCES OF VEHICLE USE INFORMATION

3.1 Introduction

In this section, actual and potential sources of vehicle use information are reviewed. The desired measure of vehicle use is vehicle miles of travel, but other measures are acceptable if they can be related to VMT by using information from other sources. It is determined whether vehicle use is, or can be, classified according to one or several dimensions of the matrix, namely:

- Trip purpose
- Trip length
- Time
  - -- Time of day
  - -- Day of week
  - -- Week, month, season of year
- Highway class
- Geographic area
- Vehicle class
- Vehicle model year (age).

Currently, there exists only one source of annually collected vehicle miles of travel information: the Federal Highway Administration. All other sources provide at best only one-time or occassional VMT estimates. However, some have basic data which can be used to derive VMT estimates.

First, the VMT estimates currently published by the FHWA are reviewed. Then, other sources are reviewed with regard to existing VMT estimates, and with regard to potential uses of their basic data. Finally, the findings are summarized, also addressing to what extent the data bases allow disaggregation along the various dimensions of the matrix.

3.2 VMT Estimates Published by the FHWA

All the states estimate the annual vehicle miles of travel (VMT) of various categories of vehicles on several categories of roads. This information is submitted to the Federal Highway Administration and published as Tables VM-1 and VM-2 in *Highway Statistics* [20]. Table VM-1 displays VMT for five vehicle classes by three highway types. At this level, VMT for passenger cars and motorcycles are not separated, only for the total on all highway systems; VMT by motorcycles are 2 percent of VMT for all passenger vehicles. Single-unit trucks and truck combinations are distinguished. Table VM-2 presents VMT by state and by 15

highway systems, but not distinguishing vehicle class. Table HT-1 also contains some information on VMT: VMT on main rural highways, separate for single-unit and for combination trucks, and by 10 regions, and Alaska, Hawaii and Puerto Rico.

The states follow different methods in developing these annual mileage estimates. The method most widely used for estimating VMT is the traffic count, which is performed at permanent and/or temporary counting stations. The counts are used to calculate average traffic density for the highway link on which they are made. Highway inventories are used to determine for which section of the highway system the selected links are representative. Total VMT is estimated by multiplying the ADT on these sections by the section lengths and summing.

The second basic method is the fuel consumption method, where the state determines the total amount of fuel "consumed" in the state based on fuel tax receipts. An average mile per gallon figure is used, which is suggested by FHWA (and possibly adjusted by the state), or is developed from a previous state study. Some states use combinations of the two methods, estimating VMT on higher level roadways through the vehicle count method and then attributing to lower level road systems the amount which would cover the balance of total state fuel consumption. Oregon uses, in addition, information from the weight/mile tax which is levied on truck operators. Since current VMT estimates are, to a large extent, based on fuel consumption, the reliability of the units-per-gallon figure used is of critical importance.

<u>The reliability of average miles per gallon figures</u>. To assess the reliability of average statewide miles per gallon figures, the following was done. For 1971 through 1975, average miles per gallon figures for each state were calculated, along with the standard deviation and ranges of these changes,* and compared with the change in the national average fuel economy figure, according to EPA. Table 3.2-1 presents the results. The figures show very little change from year to year, but the variation of changes between state is large. However, the standard deviation of the changes is fairly constant. Generally, one gets good agreement in this information, but one has to consider that the state may use EPA's figures when deriving their VMT estimates.

*This material is largely based on an unpublished report TERA, Inc. to Oak Ridge National Laboratory on *Lifetime VMT and Current State Practices to Estimate VMT* [21].

An illustration of the magnitude of potential changes is that recently New York changed the average fuel efficiency from 10.75 mpg to 11.21 mpg,* a change of 4 percent.

TABLE 3.2-1

YEAR-TO-YEAR CHANGES IN AVERAGE FUEL ECONOMY PER STATE, COMPARED WITH CHANGES IN EPA's NATIONAL AVERAGE

Years	Changes In Fuel Economy By State (Percent)			Change in EPA Fuel Economy Average (Percent)
	Range	Standard Deviation	Average	
1971-72	-5.8 to +8.2	2.3	-0.7	-1.0
1972-73	-6.4 to +4.2	2.3	-1.1	-1.3
1973-74	-5.8 to +9.4	2.9	+1.3	-1.4
1974-75	-5.3 to +11.6	2.5	+1.2	+0.9

A basic question is: how accurate can average fuel consumption figures be? Rabe [62] did investigate this question. He found that the variability between tests was 1.2 to 2.5 percent, the variability between laboratories 2.9 to 8.4 percent, and the production variability of vehicles 3.5 percent. The resulting total variability of the fuel economy figures for identical cars is 4.7 to 9.4 percent. In a later study [27], he finds somewhat lower cumulative errors of 4.6 to 6.4 percent.

CEM also analyzed data from EPA's *Gas Mileage Guide* [23] for 1973 and 1974. For a number of vehicle makes, with the same engine, carburetor and transmission characteristics, two or more mpg figures were given. For each such case, the standard deviation of the mpg figures was calculated and plotted *vs* the fuel consumption in mpg (Figure 3.2-1a and 1b). The plots suggest that the errors increase with fuel consumption, but the scatter of the points is large. On the average, the relative error was 5.7 percent for the 1973 model and 2.2 percent for the 1977 models. These figures are about half of the total errors found by Rabe, but it is not clear to what extent the EPA data are affected by differences between laboratories, and by the production variability.

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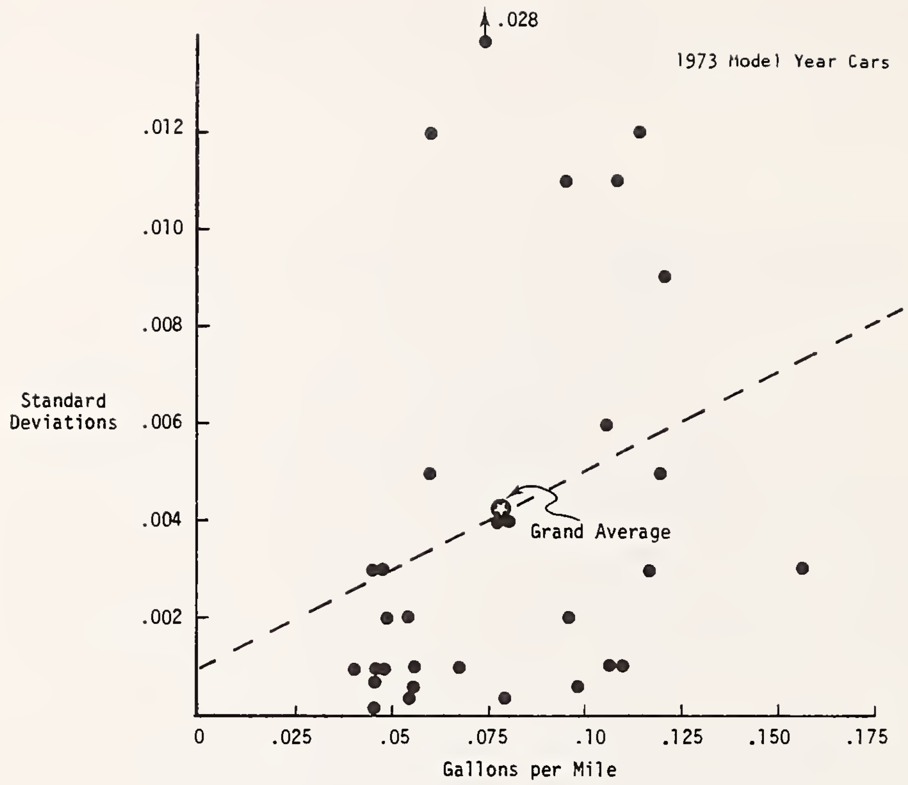
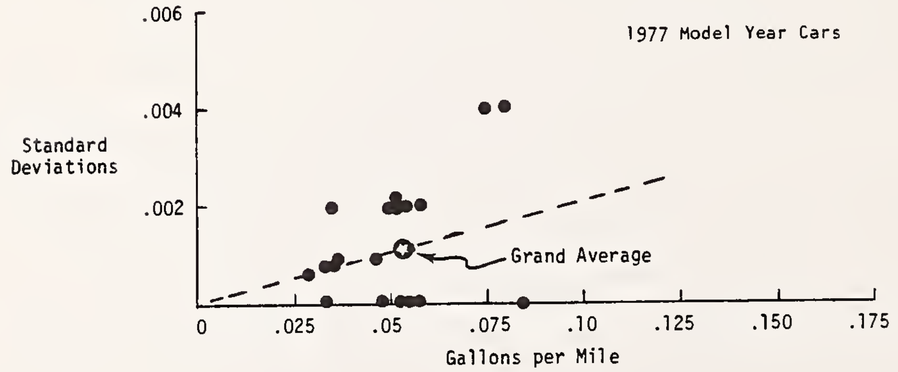
*Memorandum to all MV144A Users from Accident Records Bureau, State of New York, Department of Motor Vehicles, Office of Research and Development, April 14, 1978.

[62] Rabe, F.T., *Uncertainties in Estimates of Fleet Average Fuel Economy: A Statistical Evaluation.*

[27] Rabe, F.T., *Review of Procedures for Determining Average Fuel Economy.*



(a) The relative error for the average is 5.7%.



(b) The relative error for the average is 2.2%.

Figure 3.2-1. Standard Deviations of EPA Fuel Consumption Figures.

Each point represents the standard error of gpm estimates for a certain make/model, with a certain engine, carburetor, transmission and rear axle, derived from EPA mpg figures [23]. The broken lines are regression lines fitted to the points.

Another source of error is EPA's grouping of vehicles into inertia weight categories of 250 lbs width, for setting of the dynamometer: the vehicles may be tested under a load which may be as much as 125 lbs more or less than the one corresponding to its actual weight. Austin and Hellman [28] find standard deviations from 13 percent to 25 percent for vehicles within one inertia weight class. Much of this is due to the use of an inertia weight not corresponding to the actual weight.

In addition to the errors of the fuel consumption figures under standardized test conditions, there are the influences of variations in driving conditions, and individual driving styles. For calculating national or state averages over all vehicles, one has to consider differences in usage of vehicles by class and by age. Older vehicles are usually driven fewer miles per year, but no representative up-to-date figures are available. Thus, since vehicles of different model years often have quite different fuel consumption figures (and older vehicles may have, due to deterioration, higher fuel consumption), uncertainties in vehicle use figures can have a strong influence on national or state average fuel consumption figures.

Some of the errors, e.g., measurement errors, average out if the average fuel consumption for many different makes and models is calculated. Others, such as inaccurate assumptions about vehicle use, do not. Experience suggests that the EPA driving cycles are not completely representative of actual driving [26]. Thus, it is unlikely that VMT estimates, based on fuel consumption figures, have errors of less than 5 to 10 percent; they may be even greater.

Comparing Different VMT Estimates

The FHWA estimates VMT trends, based on traffic counts, whereas most states estimate VMT by combining traffic count and fuel consumption data. If one believes that traffic counts are a more reliable basis for such estimates, a comparison of the two types of estimates can give an idea of the reliability of VMT estimates based on fuel consumption.

The FHWA makes monthly VMT estimates, published in *Traffic Volume Trends*. Several states send the FHWA monthly traffic count data, which are used by the FHWA to make preliminary estimates of VMT figures. The change in counted traffic for each highway system is applied to the preceding year's VMT figures

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[28] Austin and Hellman, "Passenger Car Fuel Economy--Trends and Influencing Factors."
[26] O'Donnell, "Gas Mileage Figures for New Cars Get Still Another Blow."

for this highway system, to obtain a preliminary estimate. These figures for the preceding year are themselves preliminary estimates, based on the final figures for the year before. Since the states provide only annual VMT figures, FHWA uses polynomial fits, based on monthly counts, to distribute annual VMT over the twelve months.

In order to provide timely inputs for *Traffic Volume Trends*, the states send first partial or unedited data, and later additional and/or corrected data. Therefore, the monthly figures may be revised in a later edition. For example, for December 1977, the preliminary increase in VMT on main rural roads for Washington State was 2.4 percent, based on six count stations, while the revised increase was 4.1 percent, based on eleven count stations. The corresponding figures for the State of Pennsylvania are both based on 47 counting stations, a preliminary increase of 0.6 percent revised to 2.3 percent. These two states happen to be extremes, since the shifts between the preliminary and revised figures are usually zero or a few tenths of a percentage point.

For total annual figures, FHWA's estimates are close to those reported by the states. For 1975, the FHWA estimate of total VMT for the entire U.S. was within 0.9 percent of the total of the figures reported by the states. For 1976, the discrepancy was larger: the reported 1409.2 billion VMT was estimated as 1389.2 billion VMT, an underestimate of 1.4 percent. FHWA's estimate of VMT by state and highway system is usually within 10 percent of the state's figures. (The exact figures are not readily available, since comparisons between them and state estimates touch on somewhat sensitive issues.)

These figures suggest that total national VMT estimates derived from traffic counts, as used by the FHWA, and those derived by combining traffic counts with fuel consumption, as done by the states, agree within approximately 1 percent. One has to consider, however, that in FHWA's figures only the annual change is based on traffic counts. Typically,the annual change of VMT was about 5 percent, from 1974 to '75 and from 1975 to '76 it was 4 percent. Thus,a 1 percent discrepancy in the total corresponds to a discrepancy of 20 to 25 percent in the annual change,the only component of total VMT independently estimated by FHWA and the states.

Conclusions. Since currently published VMT figures are, to a large extent, based on fuel consumption figures, and average fuel consumption per mile estimates, they are subject to considerable uncertainty, possibly more than 10 percent. In addition, the only existing disaggregations are by very broad vehicle classes, or by state and highway system. Therefore, they are inadequate for quantifying the matrix. However, they might be usable for preliminary estimates where only a limited accuracy is required.

3.3 Vehicle Counting Programs

In this section, vehicle counting programs are reviewed under the aspect of using the basic data obtained from such programs for estimating nationally consistent VMT figures at a finer level of detail.

3.3.1 Description of Programs

A vehicle traffic count is a record of traffic passing the location of the counter. Traffic counting programs are important in a wide range of highway planning and evaluation tasks:

> "ADT is a fundamental traffic measurement for the determination of vehicle-miles of travel on the various categories of rural and urban highway systems. ADT values for specific road sections provide the highway engineer, planner, and administrator with essential information needed for the determination of design standards, the systematic classification of highways, and the development of programs for improvement and maintenance. Vehicle-mile values are important for the development of highway financing and taxation schedules, the appraisal of safety programs, and as a measure of the service provided by highway transportation," [4]

When placing counters, one must, therefore, consider a wide range of objectives. In this study, however, the only important aspect of the traffic counting programs is the estimation of average daily traffic (ADT) on highways. By knowing ADT and the total length of the highways to which it applies, one can estimate the vehicle miles-of-travel.

Traffic Counting Programs. State DOTs conduct traffic counting programs for a variety of highway planning and evaluation reasons. There are three major aspects of traffic counting programs:

1. The sampling plan for traffic counting (both the frequency and location of counts).
2. The collection of traffic count data (in terms of the detection and recording of vehicle travel).
3. The extrapolation of sampled data to the entire highway system.

The traffic counts are made at selected sites on roads. The sites can change from time to time, and the recording of counts can be made with differing degrees of resolution in time. The detail in the counts depends on the type of recording equipment. The three main types of counts are continuous, seasonal and coverage. They are defined as follows:

> Continuous count station. A place along a road where a traffic counting machine is installed for the purpose of counting and recording by periods not longer than one hour, the number of vehicles passing this location for continuous long periods of time, usually several years.

[4] U.S. Dept. of Transportation, *Guide for Traffic Volume Counting Manual*.

Seasonal control station. A place along a road where a traffic counting machine is installed for the purpose of counting and recording (usually by the hour) the number of vehicles passing this location for repeated intermittent periods of time. These periods, usually of consecutive seven day duration, are repeated on a predetermined schedule which divides the year into four, six or twelve equal periods.

Coverage count station. A place along a road where a traffic counting machine is installed to count the number of vehicles passing this location, usually during a consecutive period of 24 or 48 hours. Sometimes coverage counts are extended to five consecutive days, or even seven consecutive days on primary highways under 2000 ADT. Manual counts are also used for coverage count purposes [4].

In 1975, 41 State Highway Departments reported 3,500 permanent traffic counting stations [11]. They also reported 9,300 control stations where counts were taken on a less frequent basis (from one weeek/month to one week/year). Almost all states responded to the question on short counts (or coverage counts), reporting about 350,000 short count stations (which are counted from less than one week/year to once every several years). The coverage counts are often part of an overall traffic inventory program and, as such, traffic counting machines are set out in groups in order to record all travel between links of a road network. The distribution of traffic count locations varies from state to state. In Georgia, about one-third of the automatic traffic recorders are set on local rural and urban roads. In Connecticut and North Carolina, there is no automatic traffic recording on local highways and very little on secondary roads.

As a specific example, the traffic counting program in Connecticut [55] consists of:

- 32 Automatic traffic recorders (15 at toll stations).
- 25 Key stations manually operated for one day every month and also collecting vehicle classification data (large/small passenger car, 4/6/10 tired trucks, semi-trailers and buses).
- 127 portable traffic recorders (pneumatic tube type) for short-term or coverage counts.
- Special manual counting takes place with regard to route planning, etc. including turning movements and/or classification.
- Connecticut Turnpike Toll Stations provide hourly and daily vehicle volumes by vehicle type (passenger cars, 4/6 tired trucks, 3/4/5 axle trucks, and buses).

[11] Webster and Sadowski, *A Survey of State Traffic Counting Methods*.

[55] Connecticut Highway Department, *Traffic Data Available in the Traffic Statistics Section of the Division of Planning*.

The mix of permanent, seasonal and coverage counts is designed to generate the maximum amount of reliable data. As outlined in various FHWA documents [4,9,10], the equipment is distributed among roadways with similar traffic volume patterns, in terms of annual ADT and seasonal fluctuations. Also, these permanent count stations and seasonal (or control) stations are chosen to gather sufficient data within each one of these groups of highways. The coverage count data, which are normally of a more discontinuous nature, are distributed among the more stable counts from permanent and control stations. There is considerable adjustment made to coverage count data to bring it into line with longer-term data [4]. First, the coverage count data are adjusted according to daily or monthly factors. Secondly, ADTs derived from coverage counts are mapped and a manual smoothing takes place between adjacent highway links. The procedures for traffic counting differ between rural and urban roads. The rural roadways generally have a lower volume. Finally, the seasonal influence on rural highway use may be much greater. In urban traffic, the highway network is much denser and the traffic volume much heavier. The emphasis in urban traffic volume counting is the development of comprehensive urban transportation planning and model development.

Urban traffic volume counting is keyed to origin and destination studies. That is, traffic counts are taken along the screen lines and cordon lines of the O-D study. The FHWA manual [4] emphasizes the need for classification counts, turning movement, and directional flows, because of volume/capacity limitations of intersections and arterials, especially at peak hours.

At most sites, vehicle counts are made by some mechanical means. Classification counts by type of vehicle are an added feature in these counting schemes and usually require human involvement.

Most States* report hourly traffic counts to the Highway Statistics Division of FHWA each month. This information is supplied for approximately 4,000 identified counting stations.

These counts have two major uses. They are the basis of the "Traffic Volume Trends" reports, and are used to check the States' annual VMT estimates.

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[4] U.S. Dept. of Transportation, *Guide for Traffic Volume Counting.*

[9] Levinson and Roark, *Guide to Urban Traffic Volume Counting.*

[10] Bodle, *Sampling Surveys for Estimating Local Rural and Urban Vehicle-Miles of Travel.*

*As of April 7, 1978, 47 out of 51 states (including DC as a state) according to Mr. K. Welty, Planning Service Branch, FHWA.

"Traffic Volume Trends" is a monthly estimate of VMT, summarized by region, (East, Central and Western U.S.) and, separately, by road class. The estimates are produced in two steps. Within states, stations for which counts are available for the month in question and the same month one year earlier are aggregated by road class. The percent changes in the aggregate counts are applied to VMT in the earlier month to produce estimated VMT by road class within the states. The VMT breakdown is a reference VMT distribution such as the 1975 VM-2 data.

State VMT estimates are reported by the states every year. These figures are checked against the estimates obtained using the "Traffic Volume Trends" procedures on the reported counts. To avoid circularity, the FHWA estimates are corrected to match the state figures.

Traffic Counting Techniques.

The counting of traffic is divided into two basic steps, the detection of traffic units and the recording of that information. Human observers are used only for special purposes, such as classifying vehicles, counting turning, braking or weaving maneuvers, etc. Usually, automatic detection devices are used. A wide range of detection devices are available: mechanical, acoustical, optical, electrical and electronic. Baerwald [7] describes twenty vehicle detection techniques.

An important question is what is detected by a device. Some detect the passing of a wheel, thus counting axles, others detect vehicles. The latter devices may count trailers as separate vehicles.

Installation of the detectors influences reliability of performance. The most reliable detectors are the under-pavement magnetic and loop detectors. The more sophisticated devices are used to provide more detailed data such as speed or vehicle class *via* height or length.* On multi-lane roads, it depends on the installation whether vehicles passing the station at the same time in different lanes are properly counted.

Actually counting the detected vehicles is the second aspect of traffic counting. In the simplest traffic counter, an accumulating register is manually read at regular intervals. These types of recorders can be equipped with timing devices to record only during certain periods. The next type of recorder prints out a count at regular intervals on a paper tape. This tape can contain the time and totals for the interval of time. Circular graphic recorders are also available. These

[7] Baerwald (ed.), *Transportation and Traffic Engineering Handbook.*

*"The Traffic Evaluator System: An Innovative Data Collection Tool" (*Public Roads*, Vol. 40, No. 4) describes one such sophisticated device which estimates vehicle size, speed, lane changes, acceleration, etc. and records the information on magnetic tape [6].

record traffic volume for given intervals of time, according to the distance the recording pen moves out from the center of the chart as it rotates with time.

With the advent of automatic data processing machinery, more sophisticated devices have been developed which reduce the human element needed to transfer the data from one form to another. One type of recorder which provides machine readable output are punched tape recorders. Some recorders write directly on magnetic tape and others store data in a temporary memory and this memory is accessed continuously or periodically by teleprocessing equipment.

Again, there are manual methods of recording traffic volume (and class, maneuver, etc.). On low volume roads, it is feasible to use a tally sheet to record volume and other information. For higher volume roadways, manually operated counters are mounted on a board with banks of counters oriented according to the flow of traffic. This sort of counting can handle 1,000 to 1,500 vehicles per hour with less than one percent error. The ultimate system in this respect is recording of traffic *via* film or videotape. Such recordings can thus be replayed and checked. The experience in Georgia is that videotaping is not cost effective in simple counting situations, but is practical in evaluating conflict type/merging situations.

Highway Classification

Highways differ greatly in the amount of traffic they carry. Therefore, a classification of highways is necessary to estimate VMT from the length of highways and average ADT, as determined by traffic counts.

There are three basic ways of classifying highways: 1) by function; 2) by administrative responsibility; and 3) by funding. Historic highway statistics generally use the latter two classifications, but a functional classification system is being introduced.

The Federal Highway Administration organizes highways into the following categories, based on funding:

- Federal-Aid Highway Systems
  - Interstate
    - Rural final
    - Rural traveled way
    - Urban final
    - Urban traveled way
  - Other primary
    - Rural
    - Urban
  - Urban
  - Secondary
    - State rural
    - State urban
    - Local rural
    - Local urban

- Federal Aid Primary Urban Type II (TOPICS)

- Not on Federal-Aid
  - Other state rural
  - Other state urban and municipal
  - Local rural
  - Local urban and municipal.

The reporting of highway information by these categories is complicated by different classification schemes used by the states. FHWA has to reconcile the differences when producing summary statistics. The following is a quote from *1973 Highway Statistics*, which illustrates this point: "...includes mileage of county roads under state control in all counties in Delaware, North Carolina and West Virginia; 10 counties in Alabama; rural boroughs in Alaska; all but two counties in Virginia; some county mileage in Kentucky and Nevada; county roads on Federal-Aid secondary system in Montana, mileage designated as Farm-to-Market in Louisiana; and state-aid system in Maine."

The categories of the functional classification are [56]:

- Urban
  - Principal arterial system
    - -- Interstate:
      Urban extension of rural principal arterial
      Urban extension of rural minor arterial
      Other urban principal arterials
  - Minor arterial system
  - Collector street system
  - Local street system.

- Rural
  - Principal arterial system
    - -- Interstate
    - -- Other principal arterials
  - Minor arterial system
  - Collector road system
    - -- Major collector roads
    - -- Minor collector roads
  - Local road system.

Table 3.3.1-1 shows highway mileage, vehicle miles of travel and average daily traffic on the highway system according to this classification.

The Distribution of Traffic Counting Stations

For detailed estimates of vehicle miles of travel,continuous counring stations provide the best data base. The Federal Highway Administration Office of Highway Planning regularly gets about 4,100 counts from automatic traffic recorders in various states. These recorders are located on the following road systems:

[56] Sturm, *Roadway Classification Study*.

TABLE 3.3.1-1

MILEAGE, TRAVEL, AND AVERAGE DAILY TRAFFIC ON ROAD SYSTEMS IN 1975 (PERCENT IN ITALICS)

MILES OF HIGHWAY (millions)	Small Urban	Urbanized	Rural	Total Urban	Total
Interstate	1 *1*	7 *2*	30 *1*	9 *2*	39 *1*
Other Freeway -- Expressway	1 *1*	5 *1*	- *-*	6 *1*	6 *-*
Other Principal Arterial	14 *9*	31 *7*	82 *3*	45 *8*	127 *3*
Minor Arterial	17 *11*	47 *11*	153 *5*	64 *11*	217 *6*
Major Collector	18 *12*	47 *11*	431 *14*	65 *11*	802 *21*
Minor Collector			306 *10*		
Local	102 *66*	296 *68*	2,128 *68*	398 *68*	2,526 *68*
Total (million miles)	153 *100*	434 *100*	3,130 *100*	587 *100*	3,717 *100*

DAILY VEHICLE MILES OF TRAVEL (VMT)	Small Urban	Urbanized	Rural	Total Urban	Total
Interstate	20 *7*	332 *20*	321 *19*	352 *18*	673 *18*
Other Freeway -- Expressway	17 *6*	192 *11*	- *-*	208 *10*	208 *6*
Other Principal Arterial	112 *37*	457 *27*	336 *20*	569 *29*	905 *25*
Minor Arterial	68 *23*	337 *20*	342 *21*	405 *20*	747 *20*
Major Collector	34 *11*	149 *9*	350 *21*	183 *9*	635 *17*
Minor Collector			102 *6*		
Local	52 *17*	229 *14*	200 *12*	282 *14*	482 *13*
Total (million miles)	303 *100*	1,697 *100*	1,650 *100*	2,000 *100*	3,650 *100*

AVERAGE DAILY TRAFFIC (ADT)	Small Urban	Urbanized	Rural	Total Urban	Total
Interstate	20,000	47,000	11,000	39,000	17,000
Other Freeway -- Expressway	17,000	38,000	-	35,000	35,000
Other Principal Arterial	8,000	15,000	4,000	13,000	7,000
Minor Arterial	4,000	7,000	2,000	6,000	3,000
Major Collector	2,000	3,000	800	3,000	800
Minor Collector			300		
Local	500	750	100	700	200
Average	2,000	4,000	500	3,400	1,000

Source: Derived from *National Functional System Mileage and Travel Summary* [8].
Note: Data might not sum exactly, due to rounding.

		Percent
1.	Rural Interstate	16.4
2.	Urban Interstate	11.5
3.	Rural Primary (other)	35.0
4.	Urban Primary (other)	11.4
5.	Rural Secondary	9.8
6.	Urban Secondary	1.6
7.	Rural Local	2.3
8.	Urban Local	0.8
9.	Federal Air Urban	1.4
10.	Other State Rural*	1.1
11.	Other State Urbanized Municipal*	1.2
12.	Other Local Rural*	1.3
13.	Other Local Urban*	5.4

As one can see, the majority of these counters are on interstate and other primary road systems. On the urban interstate system, there is approximately one recorder every 20 miles of highway. At the other extreme, on the local rural system, there is less than one automatic recorder for every 10,000 miles.

3.3.2 Errors of VMT Estimates from Traffic Counts

Sources of Errors

VMT estimates from traffic counts are subject to two kinds of errors: (1) errors of data collection and reduction; and (2) errors due to the sampling system.

There are two sources of error in the data collection and reduction. The first is the mechanical limitations of vehicle detecting and recording devices. According to the *Transportation and Traffic Engineering Handbook* [7], this is usually less than two percent. The second source of error is the conversion of axle counts to vehicle counts, as most pressure sensitive detectors count only axles.

Most State Highway Departments conduct vehicle classification programs. The purposes of such programs are not to provide estimates of the frequency of multi-axled vehicles for adjustment axle count data, but stress studies of highway wear and tear, safety, etc. [14,15]. The problem of misestimating vehicle

*Non-Federal Aid system

[14] Wisconsin DOT, *Vehicle Classification Survey Data Collection Methods and Analysis.*

[15] Wisconsin DOT, *Vehicle Classification Data User Demand.*

numbers is minimal because the absolute number of trucks with three or more axles is very low, between three and five percent of total truck sales between 1970 and 1976 [16]. Tractor sales represent about 20 percent of truck sales (or 3 percent of total vehicle sales). Even considering their higher annual mileage, one would not expect three (or more) axled vehicles to represent more than 5 percent of the traffic stream. However, this is not necessarily true for specific situations. A review of vehicle classification data from Connecticut, Maine, North Carolina and Georgia reveals that some highways have tractor-trailer activity of 10 percent or more; this was particularly true on low volume Interstates in Maine. Even then, errors in vehicle classification have a small influence on the conversion of axle counts into vehicle counts. If 11 percent of all vehicles had four axles, but one used 10 percent erroneously, the effect on the vehicle count estimate would be only 1 percent.

There are two sources of sampling errors. One is due to the sampling of highway locations for counting, the other to the sampling at one location. The latter error can practically be eliminated--except on very low volume roads--by continuous counting. However, using a limited number of counters will increase errors due to the sampling of locations. A common strategy for reducing these errors (without unduly increasing the sampling error at each location) is to stratify samples according to similarities of the roadway. The *Guide to Urban Traffic Volume Counting* [9] recommends:

1. Urban traffic follows daily and hourly variation patterns which are generally consistent and often predictable. Urban traffic volume patterns exhibit relatively little weekday and seasonal variation. The percent of total traffic occurring in any given period is approximately the same along any route.

2. The more counts, even though of very short duration, the greater the reliability of the resulting estimate. Similarly, the heavier the traffic volume at a particular location, the greater the reliability of a given sample.

3. The distribution of counts throughout a day is more significant than the total time during which the traffic is counted. The number of separate and independent observations is more important than the number of hours of each observation.

4. As counting locations are combined, the sampling variability resulting from short-counts diminishes.

5. Stratified sampling techniques have merit over simple random sampling in estimating VMT, since they reduce the variation within parts of the total sample.

[16] MVMA, *Motor Vehicle Facts and Figures.*
[9] Levinson and Roark, *Guide to Urban Traffic Volume Counting.*

6. Sampling more locations, each for a shorter period of time, will likely result in less error than sampling a few locations, each for a longer period. This implies maximizing the number of different locations sampled.

This report also suggests that because the coefficient of variation of traffic volume estimates differs between freeways and arterial highways, and because these spatial variations exceed the temporal variations (monthly, weekly, or seasonal), stratified sampling procedures will substantially reduce overall spatial variance and sample size requirements. Freeways exhibit coefficients of variation of 50-80 percent and arterials of 80-120 percent, when randomly sampled. With stratified sampling, the variations can generally be reduced to 30 percent or less.

In reality, sampling plans are often based on experience and specific knowledge of the highway system, which highway officials have. For instance in 1963, Israel Zevin of the Connecticut Highway Department wrote:

> "The selection of the permanent traffic recorders to use for the expansion of the coverage counts is dependent upon the judgment of an individual familiar with the characteristics of the recorders and the section of road being counted. This judgment is based on years of experience in traffic counting and traveling throughout the State. Thus, if a knowledgeable individual is not available to exercise judgement, large errors are likely to occur in the determination of the average daily traffic. It is a rather difficult task to train personnel to understand the traffic characteristics of the recorders and roads throughout the State [13]."

In 1970, the Federal Highway Administration issued the *Guide for Traffic Volume Counting Manual* [4]. In 1973, *Sampling Surveys for Estimating Local, Rural and Urban Vehicle-Miles of Travel* [10] was published. In 1975, the *Guide to Urban Traffic Volume Counting* was issued [9]. Currently, a new study is being conducted by John Hamburg and Associates on improved methods of state traffic volume counting (NCHRP Project 8-20). This illustrates that the state-of-the-art of traffic estimation is still in flux.

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[13] Zevin, *Sampling Techniques for Traffic Counting in Connecticut.*

[4] U.S. Dept. of Transportation, *Guide for Traffic Volume Counting Manual.*

[10] Bodle, *Sampling Surveys for Estimating Local, Rural and Urban Vehicle-Miles of Travel.*

[9] Levinson and Roark, *Guide to Urban Traffic Volume Counting.*

Assessing the Numerical Accuracy of VMT Estimates from Traffic Counts

To rigorously estimate the errors of VMT figures derived from traffic count data requires an analysis of the actual count data. However, certain rough estimates can be made from available information.

Four pilot studies to estimate VMT from samples of traffic counts are described by Bodle [10]. Two different sampling procedures were used. The relative errors of the estimates are presented in Table 3.3.2-1.

TABLE 3.3.2-1

RELATIVE ERRORS OF VMT ESTIMATES OBTAINED FROM TRAFFIC COUNT SAMPLES [10]

Study	System Type	Range of Estimated Relative Errors	Total of Estimated Relative Errors
Colorado (1970-1972)	Local rural	2.2% to 100%	31.1%
Colorado (1971-1972)	Local urban	0.7% to 98.6%	8.3%
	Local combined	2.5% to 86.3%	11.7%
Oregon (1969-1970)	County roads	2.4% to 99.5%	26.9%
Wisconsin (Oshkosh, 1969)	All urban--10 volume groups	7.2% to 52.4%	6.9%
Idaho (15 cities over 5000 - 1958)	All urban--9 volume groups	5.2% to 11.0%	6.9%

The meaning of the "Range of Estimated Relative Errors" differs between the studies. In the Colorado and Oregon studies, it is the range of errors of estimates derived from counts for weekly periods in sample areas. In the Wisconsin and Idaho studies, it is the range of errors of estimates for highways in different traffic volume groups, derived from samples of daily counts. Also, the scope of the counting programs varies. On the Colorado rural roads, there were 20 counting stations over a year, corresponding to one station year per 3300 road miles; on the urban roads, 20 counting stations over a year, corresponding to one station year per 380 miles. On the Oregon County roads, the equivalent of 18 counting stations per year was used, or one station year per 1800 road miles. In Idaho, the equivalent of six year-round counting stations was used, or one station year per 550 miles. These figures are estimated on the basis of highway mileage figures in *Highway Statistics*. For the Oshkosh area, one finds the equivalent of three year-round counting stations, or one station year per 5000 road miles, using the street mileage given in [10], but this figure appears implausible. In general, one may draw the speculative conclusion that "practicable" counting programs can achieve a standard error of 7-8 percent for VMT on urban streets in a state, and of about 30 percent for local rural roads within a state.

[10] Bodle, *Sampling Surveys for Estimating Local Rural and Urban Vehicle-Miles of Travel.*

However, even if VMT estimates for one highway class in one state are subject to large errors, national aggregates for each highway class, and even more total national VMT estimates will be better, if the estimates made by each state and consequently their errors, are independent.

Assume that the VMT on a certain highway system in state i are V_i and are known with a relative error of ε_i, whose expected value $E(\varepsilon_i) = 0$, and whose variance $E(\varepsilon_i^2) = \sigma_i^2$. For the total VMT for the entire country, V and its relative error, ε_T, the following holds:

$$\sum_{i=1}^{51} V_i(1 + \varepsilon_i) = V(1 + \varepsilon_T).$$

Now $\varepsilon_T = \frac{\Sigma V_i \varepsilon_i}{V}$ and we have $E(\varepsilon_T) = 0$, and $E(\varepsilon_T^2) = \frac{\Sigma V_i^2 \sigma_i^2}{V^2}$ assuming all the state ε_i's are uncorrelated. The national total, therefore, has a variance of:

$$\sigma_T^2 = E(\varepsilon_T^2) = \frac{\Sigma V_i^2 \sigma_i^2}{(\Sigma V_i)^2}$$

If one can assume that the relative errors of all states have the same variance, $\sigma_i = \sigma$, then

$$\sigma_T^2 = \sigma^2 \frac{\Sigma V_i^2}{(\Sigma V_i)^2}$$

holds. Using the FHWA's estimates of total VMT on all highways in all states in 1973, one obtains

$$\frac{\Sigma V_i^2}{(\Sigma V_i)^2} = 0.038.$$

Thus,

$$\sigma_T = \frac{\sigma}{5.13}.$$

This relation would also hold for the relative errors of VMT estimates for specific highway systems, as long as the distribution of VMT over the different highway systems were the same in all states. However, even if this also does not hold strictly, the relation $\sigma_T = \sigma/5$ may be used as a first approximation.

Thus, if one uses the above estimates for the standard errors of one state's VMT figures for local rural roads, one obtains a potential error for national VMT figures on local rural roads of about 6 percent and for local urban roads of about 1.5 percent.

Another approach to estimating the potential errors of VMT figures derived from traffic counts is the following. Consider a certain highway system on which there are n counters. For continuous counting stations, the error due to the fluctuations of traffic is small; what is important is that of all highway segments which may have different traffic volumes, only n segments are sampled, one by each counter. (It would be unreasonable to place more than one counter on each section.) Assume that traffic volume on the many segments follows a distribution which has a standard deviation σ. Then, the standard deviation of an average traffic volume n derived from a sample of n counters is:

$$\sigma(\mu) = \sigma/\sqrt{n}$$

and the relative error of the average traffic volume μ is

$$\sigma(\mu)/\mu = (\sigma/\mu)/\sqrt{n},$$

where σ/μ is the coefficient of variation of traffic volume on the highway system considered.

Table INT-15 in *Highway Statistics* gives the volume distribution of divided highways with full access control, as well as for undivided highways, separate for rural and "municipal extensions" (urban). From these figures for 1974, coefficients of variation were calculated. They are shown in Table 3.3.2-2. We assumed that the values for undivided highways hold for all non-Interstate highways (and we assumed that essentially all divided highways with full access control are Interstate Highways). The table shows the number of counters per highway system, the estimated VMT (from Table 3.3.1-1) and the resulting relative errors. If we consider that the two studies of rural areas mentioned above achieved relative errors of about 30 percent with 18 to 20 counting stations, and that 250 stations would reduce the error by a factor of $\sqrt{250/19} = 3.6$, we find excellent agreement with the 8 percent for local rural roads shown in Table 3.3.2-1. For the local urban streets, between 3 and 20 stations gave errors of 7-8 percent. This is a major discrepancy against the findings as shown in Table

TABLE 3.3.2-2

DATA USED TO ESTIMATE THE RELATIVE ERROR OF VMT FIGURES OBTAINED FROM TRAFFIC COUNTS

Highway System	Rural					Urban			Combined	
	Number of Counters	Daily VMT	Coefficient of Variation of Traffic Volume	Relative Error of VMT Estimate (%)	Number of Counters	Daily VMT	Coefficient of Variation of Traffic Volume	Relative Error of VMT Estimate (%)	Daily VMT	Relative Error of VMT Estimate (%)
Interstate	470	321	0.85	4	670	352	0.605	2	673	2.2
Other Primary & Prin.Arteries	470	336	1.30	6	1430	777	1.03	3	1113	2.8
Minor Arteries	65	342	1.30	16	400	405	1.03	5	747	7.8
Collectors	110	452	1.30	12	45	183	1.03	15	635	9.6
Local	250	200	1.30	8	150	282	1.03	8	482	5.7
Total		1650		5		2000		2.4	3650	2.6

3.3.2-2 that 150 counting stations would give a relative error of 8 percent. A speculative explanation is that the coefficient of variation of traffic volume on local urban streets is smaller than assumed in Table 3.3.2-2. This suggests that the error estimates in the table are realistic or possibly even conservative.

However, one has to consider that this argument assumed truly random sampling. There are reasons to assume that the counting stations do not constitute a purely random sample, even within each highway system. Rather, special problems might lead to the selection of certain counting stations. This may bias the results in a way which is not easily ascertainable.

3.3.3 Uses of Vehicle Counting Data

We have found that extensive continuous vehicle counting data exist. From these data, together with highway inventory data, VMT can be estimated by state, by highway system by time of day, day of week and month or season of the year. These data can also be disaggregated by vehicle type, using data from classification counts.

On the basis of available information, we estimate that total national VMT can be estimated with a relative error of as little as 3 percent. VMT figures for Interstate and other primary highways have similar errors, but for lower order highways, the errors will be much larger. If one further disaggregates by state, errors of 30 percent and more can easily occur. In addition to these random errors, biases might be present.

3.4 Nationwide Personal Transportation Study

3.4.1 Description of the NPTS

The Nationwide Personal Transportation Study was conducted by the Bureau of the Census for the Federal Highway Administration (FHWA) once in 1969-70 and again in 1977.

The 1969-1970 NPTS is based on a sample of 6,000 households, approximately one-half initially interviewed in April 1969 and the other in August 1969. The first group was interviewed four times (April, July, October 1969, and January 1970) and results from this group were expanded to represent annual estimates of trips and travel by automobile. The data collected are:

1. Household Identification: Area, household characteristics, dates, etc.
2. Automobile Record: Number, purchase information, general usage, etc.
3. Shopping: Frequency, seasons, availability of public transit.
4. Travel to Work: Distance, mode, etc.
5. Driver Information: Mileage.
6. Travel to School: Mode, distance.
7. Travel Day Report: Every trip is recorded. A trip is defined as "anytime you went from one place to another by motor vehicle or some form of public transportation." (Source: 1969-70 NPTS Questionnaire)
8. Overnight Travel: Any overnight trip during the past seven days.

Between 1972 and 1974, FHWA published eleven reports based on the 1969-70 NPTS:

1. Automobile Occupancy
2. Annual Miles of Automobile Travel
3. Seasonal Variations of Automobile Trips and Travel
4. Transportation Characteristics of School Children
5. Availability of Public Transportation and Shopping Characteristics of SMSA Households
6. Characteristics of Licensed Drivers
7. Household Travel in the United States
8. Home-to-Work Trips and Travel
9. Mode of Transportation and Personal Characteristics of Tripmakers
10. Purposes of Automobile Trips and Travel
11. Automobile Ownership.

The 1969-70 NPTS had a rather small data base from which to project national totals. Also, the amount of information on longer trips was limited by restricting the reporting of overnight trips to a seven-day period.

The 1977 NPTS is considerably expanded from the 1969-70 study in terms of sample size and number of questions. The 1977 NPTS is being conducted as part of the 1977 National Travel Survey (which was previously done in 1972 and 1967 and deals primarily with longer trips). The sample for the NTS is approximately 25,000 housing units. About 18,000 of the 25,000 sample households are used for NPTS and were also interviewed for the Current Population Survey. Nearly 14,000 of these are a nationally representative probability sample and the remaining 4,000 are a probability sample of households in specific areas of the country in order to increase the reliability of trip data for these areas. (The sample of housing units includes students living in college dormitories.) The remaining 7,000 households used in NTS but not NPTS are part of the Current Quarterly Housing Survey. The selected population of households is only a small subset of all possible households (less than one-half of one-tenth of one percent). Each household was visited several times during 1977; therefore, there is the potential for consistency checks and internal accuracy of the data to be evaluated.

The areas selected for participation include 376 primary sampling units (PSUs) from the Current Population Survey, and 103 PSUs from the Quarterly Housing Survey. (A PSU is a county, group of counties or independent city.) The estimates which will be produced in the studies of the 1977 NPTS will be based on a complex, multi-stage ratio estimation procedure. The procedures used by the Bureau of the Census take into account individuals or households which were not obtained, adjustment of the sample population to total population characteristics, etc. There are two types of errors which can be associated with the estimates: sampling and nonsampling errors. The particular sample used in the survey is chosen from a large number of possible samples of the same size that could have been selected, using the same sampling design (sampling error). Nonsampling errors represent response or enumeration errors. The standard errors of the estimates approximate both the sampling and nonsampling errors. The data coding from the latest NPTS were scheduled to be completed June/July 1978. However, there has been continuing slippage of the date when NPTS data will be available. According to the Bureau of the Census, the current best estimate is early to mid-1979.*

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*John Cannon, Bureau of the Census, Personal Communication, May 1978.

The basic data collection form for NPTS is 19 pages long, with a three-page supplement on trips that get mapped (Forms NTS-2 and NTS-2A). Figure 3.4.1-1 shows the structure of the information collected from each household during one visit. A few points need to be elaborated.

As part of the household information, detailed data on "household vehicle" are collected, including estimates of annual mileage. "Household vehicles" are all vehicles which are "regularly available" for household use, irrespective of ownership, and include leased vehicles, certain company cars, vehicles used primarily in business, but available for household use, etc. Most, however, are likely to be owned by household members.

To estimate the number of vehicles falling into each category of ownership or use, the following sources were consulted:

- *Motor Vehicle Facts and Figures* (MVMA) [16]
- *Highway Statistics* (FHWA) [20]
- *Truck Inventory and Use Survey* (Bureau of the Census)[29]
- *Survey of Purchase and Ownership* (Bureau of Labor Statistics) [30]
- *Taxicab Operating Characteristics* [31]
- Also data on fleets [32,33].

Based on an analysis of the data in the above sources, CEM estimates that of the 107 million registered passenger cars in 1975, the ownership breakdown is:

• Household ownership	∿	95%	101 million
• Business ownership	∿	4%	4 million
• Government ownership	∿	1%	1 million.

In addition, based on fleet owner data from *Motor Vehicle Facts and Figures* [16] approximately one-half of the business ownership of passenger vehicles is a lease/rental type arrangement.* Review of the DOT study on taxis reveals only

[16] MVMA, *Motor Vehicle Facts and Figures.*
[20] Dept. of Transportation, *Highway Statistics.*
[29] Dept. of Commerce, *1967 Census of Transportation.*
[30] Dept. of Commerce, *1973 and 1974 Surveys of Purchases and Ownership.*
[31] Dept. of Transportation, *Taxicab Operating Characteristics.*
[32] *Commercial Car Journal,* "Census of the Motor Fleet Market, A Statistical Analysis."
[33] Hertz Corporation, *Motor Vehicle Operating Costs and Fuel Usage in the United States.*

*Estimates by the Hertz Corporation [33] were that total fleet cars represented 10 percent of the total 1975 passenger car population, of which 4 percent were lease/rental types. Also, they estimate that one of every five new cars sold in 1975 was a lease/rental unit. This seems to grossly contradict the U. S. Census *Survey of Purchases and Ownership* and also fleet-owner reporting.

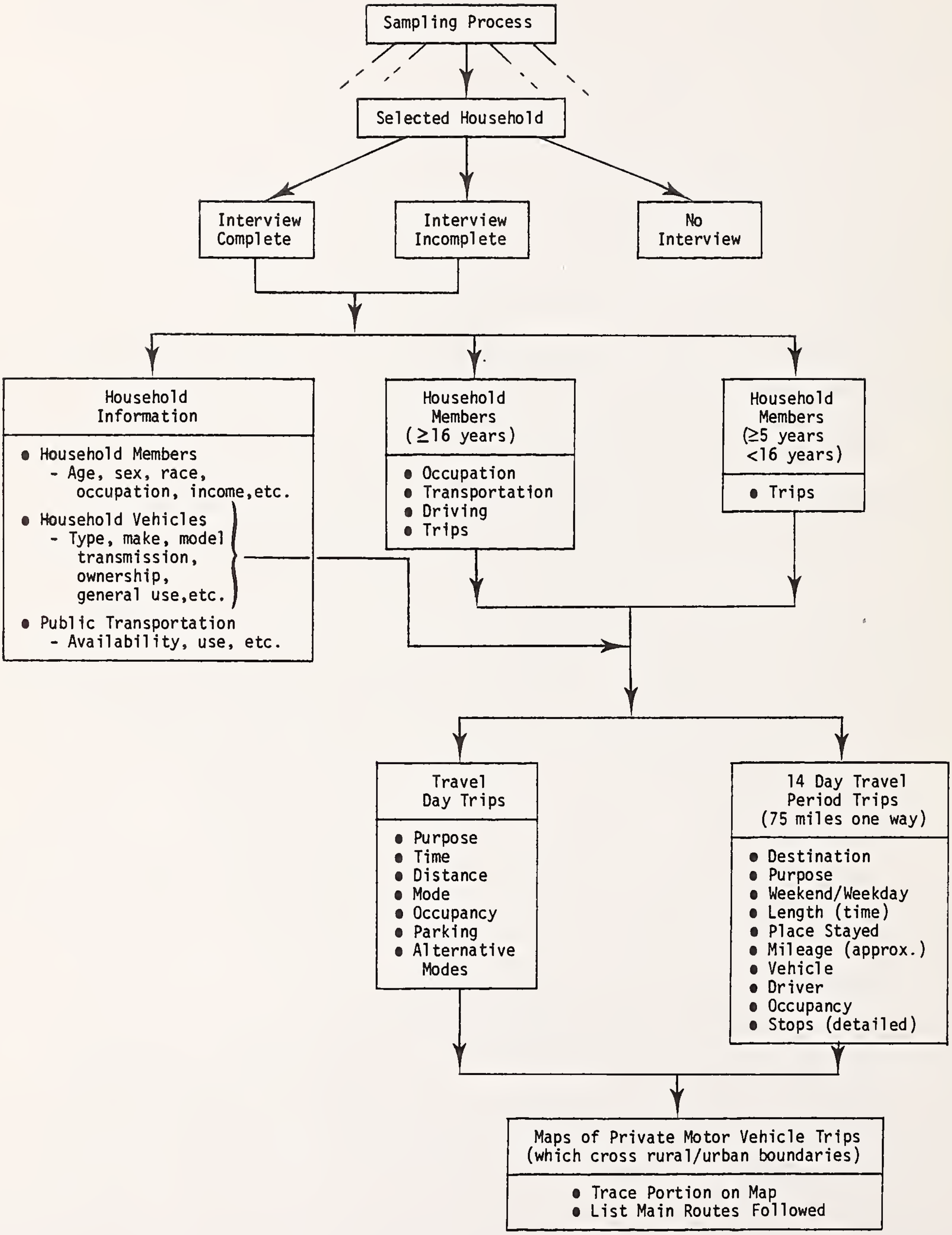

Figure 3.4.1-1. Structure of Information Collected in the 1977 Nationwide Personal Transportation Study.

about 200,000 taxicabs or less than 0.2 percent of the passenger vehicle population [31]. One problem noticed in analyzing the data was that the number of publicly owned vehicles differs considerably between the amount reported in *Highway Statistics* [20] and the amount reported by fleet owners and recorded in *Motor Vehicle Facts and Figures* [16], which are respectively 641 thousand and 231 thousand (excluding military). However, it seems unlikely that the government total exceeds one percent of all passenger vehicles.

With regard to light duty vehicles (pickups, vans, utility vehicles) there has been an increase in sales of the under 10,000 pound GVWR categories from about 83 percent of truck sales in 1971-74 to about 88 percent in 1975-76. Therefore, of the 26 million trucks registered in 1975, approximately 22 million are light duty vehicles (85 percent). There are considerable gaps in the data on the ownership and use of these vehicles. However, our best estimates of ownership are:

• Household ownership	65% (or more)	14 million
• Business ownership	30% (or less)	7 million
• Government ownership	5%	1 million.

In summary, therefore, the majority of passenger cars and light duty vehicles are used for personal transportation, with perhaps 10 percent of the total passenger vehicle population (about 5 million cars and 8 million light duty vehicles out of 139 million cars and light duty vehicles registered in 1975).having business or government ownership and mixed usage. Some portion of the travel of this 10 percent would <u>not</u> be described in NPTS.

For each licensed driver, an estimated annual miles of driving is obtained. In addition, Question #30 on Form NTS-2 deals with work-related travel, i.e., it asks whether driving is an essential part of the respondent's work (e.g., bus drivers, delivery man, etc.) how much work-related driving was done on the travel day, how much is done on an average day, and how often it is done. However, no further details are collected on work-related driving. With the exception of military drivers, the sample should be representative of all licensed drivers.

The most extensive information is collected on "trips" on a certain day. Travel--by any means--from one address to another constitutes a trip. This definition excludes joyrides which begin and end at the same address. Among the information collected is what the trip purpose was, origin and destination, estimated distance, travel time, and time the trip began. If a household vehicle

was used, it is referenced; otherwise only vehicle type is given. If a trip crossed on urban/rural boundary, a trip may is made.

Information on longer trips--over 100 miles--is collected for those occurring during a 14-day period, rather than during a certain "travel day." Actually, the information is collected for trips of more than 75 miles, but edited to include only trips of more than 100 miles.

3.4.2 The Reliability of Estimates Based on the NPTS

There are three sources of errors for VMT estimates based on the NPTS data: (1) the sampling variation; (2) non-sampling errors, such as biases due to no response, exclusive of joyrides, probable lack of information on driving by unlicensed drivers, etc.; and (3) errors due to the subjective nature of the annual VMT estimates and trip length figures given by the respondents.

Errors of the first kind can be estimated from the sampling plan. The Census Bureau tries to avoid errors of the second kind by appropriate design of the collection process, although some of these errors remain. These latter, and errors of the third kind can be estimated only by comparisons with other data sources, or possibly by checking the internal consistency of different estimates made within NPTS.

We have performed several simple analyses to obtain some estimates of the potential errors of the 1969-70 NPTS. These findings cannot be directly applied to the 1977 NPTS. However, because the sample is three times as large as in the 1969-70 NPTS, one can expect the sampling variation to be approximately reduced by a factor of $1/\sqrt{3} = 0.57$. The exact reduction, however, depends on the details of the sampling design.

Comparison of Total VMT Estimates

NPTS Report No. 7 (*Household Travel in the United States*) estimates that residents of households took 87 billion trips in which an automobile or taxi was the only transportation mode. These trips accounted for an estimated 776 billion vehicle miles of travel. The Federal Highway Administration estimates 850 billion VMT for passenger cars in 1969, and 891 in 1970 (*Highway Statistics*). The difference of 9 to 13 percent may be due to non-household travel in passenger cars.

The NPTS data show 67 million household passenger vehicles, whereas the states reported to the FHWA a total of 86 million and 89 million private and commercial automobiles in 1969 and 1970, respectively. The difference is 22 to 25

percent. Again, at least part of this may be due to the exclusion of non-household passenger cars in the NPTS. It is surprising, however, that the discrepancy in the number of vehicles is much larger than the discrepancy in the total mileage. This would imply that non-household cars have a lower annual mileage than household cars.

The explanation offered in the NPTS report for the discrepancy in the aggregate numbers is that most drivers "tend to underestimate the amount of driving they do." Other reasons they give for the discrepancy are (1) the omission of military personnel (in NPTS); (2) the exclusion of nonlicensed drivers; (3) the restriction to passenger car or taxi as the sole method of transportation. However, it would seem that drivers might be overestimating their mileage when one considers the number of vehicle miles which would be estimated from the product of NPTS average vehicle mileage (11,600 VMT) and state reported registered vehicles (87 million). This result (1.01 trillion VMT) is 3 to 19 percent higher than the 850 and 891 billion VMT estimated by the states and reported in *Highway Statistics* for 1969 and 1970, respectively.

NPTS Report No. 7 indicates that there was an average of 3.4 trips per day, resulting in 34 vehicle miles of travel. This results in 12,400 VMT per household. Report No. 2, as stated above, estimated 11,600 VMT per vehicle. This breaks down into 10,800 VMT per vehicle in one-car households; 12,000 VMT per vehicle in two-car households; and 12,800 in three-or-more car households. If we combine these VMT with the relative frequencies of such households (48%, 26% and 5% respectively and also assuming only three cars for the last group) then the average household VMT would be 13,300. The difference between these two NPTS estimates (12,400 and 13,300 VMT per household) is 7 percent.

Also, the NPTS's estimate of 11,600 annual miles of travel per vehicle is by 16 to 19 percent higher than the FHWA's estimates of 9,782 and 9,978 for 1969 and 1970, respectively.

Not all these discrepancies indicate errors of the NPTS figures. Some might be explained by differences in coverage of vehicles, as indicated. Other sources of potential errors are the states' procedures for estimating VMT, and even the registration files, which are not necessarily up to date.

Comparing VMT Estimates Using Different Model Year Distributions

NPTS (Report No. 2) gives the distribution of cars by model year, and the average annual mileage by model year (shown in Table 3.4.2-1). Combining these results in an average of 11,600 annual miles per passenger car. The distribution

TABLE 3.4.2-1

DISTRIBUTION OF AUTOMOBILES BY MODEL YEAR AND ANNUAL VMT BY MODEL YEAR

Model Year	NPTS (April and August 1969)		R.L. Polk data-July 1, 1969
	Average Annual Miles (Thousands)	Percentage of Automobiles	Percentage of Automobiles
1969	17.6	8.3	8.2
1968	16.2	12.2	11.4
1967	13.2	10.9	10.3
1966	11.5	11.5	11.2
1965	11.7	12.1	11.3
1964	10.0	9.6	9.6
1963	10.4	8.7	8.7
1962	8.7	7.3	7.4
1961	10.9	4.5	5.2
1960	8.0	4.1	4.8
$\leq$ 59	6.6	10.8	11.9

of cars by model years according to R.L. Polk registration data is also shown in Table 3.4.2-1. The differences between these and the NPTS data are very small; the automobile population in the NPTS sample is less than a half year younger than the population in the R.L. Polk data. Average annual mileage per vehicle calculated on the basis of the R.L. Polk model year distribution, however, is 10,200; that is 12 percent less than the NPTS estimates.

Comparing Subjective VMT Estimates with Odometer Readings

All mileage estimates in the NPTS are based on respondents' estimates of miles, wither total annual miles of travel or trip length. Thus, the results rely heavily on the reliability of these estimates. House and Waller in *Accuracy of Driver's Estimate of Vehicle Mileage Driven* [34], compared subjective (monthly) mileage estimates and actual mileage, based on vehicle odometer readings for 505 drivers. The average actual mileage was 909 miles per month (or 10,900 per year). On the average, the drivers underestimated mileage by only 7 percent; however, the errors had a standard deviation of 318 miles (per month). (House and Waller also studied the influence of various factors and found, among others, that male drivers tended to overestimate and female drivers underestimated their monthly mileage.) White *et al.* [35] compared annual VMT from odometer readings made

[35] White, *et al.*, *Improved Exposure Measurements*.

during annual inspections with owners' estimates of annual VMT. This study of 434 North Carolina owners showed their average annual mileage was 9,946, that owners overestimated (on the average) by only 3 percent, but that the standard deviation of the annual estimate was 6,224 miles!

In the first case, the 7 percent error (64 miles) of the average exceeds by far the standard error to be expected from the standard deviation of the individual estimates ($318/\sqrt{505} = 14$ miles), so one can strongly suspect a downward bias. In the second case, however, the 3 percent error of the average (300 mi) is equal to what one expects from the standard deviation of the individual estimates ($6224/\sqrt{434} = 300$ miles). Thus, there is no suggestion of a bias, though the data are still compatible with a bias of -7 percent.

Analyzing Home to Work Trips

The preceding arguments were based on mileage figures only. Here we present an argument which uses both time and distance information. This allows one to estimate average trip speed, and, thereby, assess the plausibility of the basic figures. The NPTS Report No. 8 (Home-to-Work Trips and Travel) reports the average home-to-work commuting time by trip length. Plotting these data (Figure 3.4.2-1) reveals the following features:

(1) The relation appears piecewise linear, with the following segments:
   - 1/2 through 2 miles
   - 3 through 10 miles
   - 11 or more miles.

   The separation between the last segments is not sharp; it might also be made at 11 or 12 miles.

(2) Extending the first segment to 0 miles distance would result in a travel time of five minutes.

(3) The time for 13 miles is inconsistent with other data. For each SMSA size class, it is lower than the time for 12 mile distances.

Item 3 might be an effect of superstition about the number 13. This explanation is, however, not quite satisfactory; that 1.5 percent of all workers report a distance of 13 miles agrees well with 1.5 reporting 16 miles, and 8.7 reporting 15-19 miles, but it contrasts with 4.3 percent for 12 miles (but only 1.5 for 11 miles). Five and ten miles also have extensive frequencies. Overall, the travel time for 13 miles should be considered with suspicion, and 5, 10 and 12 miles are apparently overreported. Such a preference for reporting "round" numbers is well known.

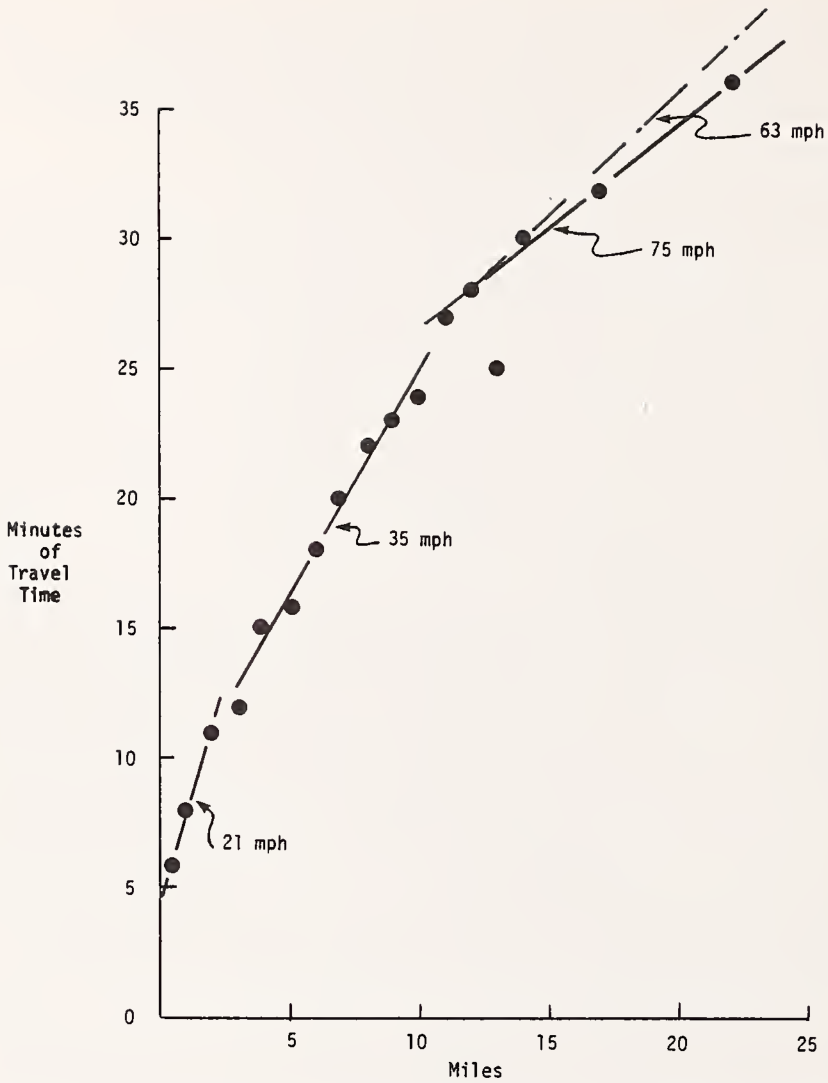

Figure 3.4.2-1. Home-to-Work Trip Length vs. Elapsed Time.

The slopes of the straight lines correspond to the indicated travel speeds. The broken line corresponds to the points if the last two were shifted to the lower ends of the corresponding distance intervals.

Source: NPTS Report No. 8: Home-to-Work Trips and Travel.

Item 2 becomes understandable if one reads the question carefully: "How much time is usually required for....to get to work from the time he leaves until he arrives at work?" Apparently, respondents included into their time estimate the time to get from the house to the car, start it, etc. and, on the other end of the trip, to park it and to walk to their place of work. Therefore, this time would have to be excluded when estimating travel speed.* The slope of the

*This was not done by Austin and Hellman [36] in "Passenger Car Fuel Economy as Influenced by Trip Length." Therefore, they found improbably low average speeds for short trips: 2.5 mph for trips up to 1/2 mile, and 7.5 mph for trips of one mile length.

segments corresponds directly to the average travel speed. A look at those linear segments mentioned in Item (1) shows the following:

- The points for 1/4, 1 and 2 miles are practically perfectly on a straight line, its slope corresponding to 21 mph.
- The points from 2 through 10 miles (even as far as 12 mi) scatter very little around a straight line, the slope of which corresponds to 35 mph.
- The points for 11 through 24 miles are, with the exception of that for 13 miles, very close to a straight line with a slope corresponding to 75 mph.

This pattern suggests the following: very short trips, and the first and/or last leg of longer trips are made on urban streets or secondary suburban or rural roads, for which an average travel speed of 21 mph appears plausible. For longer trips, up to 10-12 miles, the rest is traveled on urban arteries or primary rural roads, with an average travel speed of 35 mph, which also appears plausible. For trips of more than 10 or 12 miles, the data suggest that the additional distance is traveled on high-speed roads. However, the speed of 75 mph (corresponding to the slope) appears implausible, especially for commuter traffic. Including the point for 13 miles decreases the average speed slightly. Also, the last two points apply to the intervals 15-19 and 20-24 miles. Shifting the points to the lower limits of the intervals also reduces the average speed. However, even combining both effects reduces the average speed only to 63 mph. This is much more plausible than 75 mph, but still appears to be high for commuter traffic.

Since commuters usually know their commuting time quite well, because they need it for planning their home-to-work trips, it is plausible to assume that they tend to overestimate their commuting distance, at least for longer trips. If so, that would explain the high average speed found. Average travel speed of passenger cars in free-flowing traffic on all main rural roads was 61 mph in 1969 (FHWA, *Traffic Speed Trends*), and 66 on completed rural Interstate Highways, but only 58 on completed urban Interstates, 61 on completed suburban Interstates, and 42 on urban primary and 50 on suburban primary. All these figures apply, however, only to free-flowing traffic which cannot necessarily be expected for commuter traffic. A travel speed of 50 to 60 mph appears plausible for commuter traffic on these types of roads. Thus, it appears that commuters may overestimate their commuting distance by somewhere between 5 and 25 percent, at least for distances beyond 10 miles.

Errors in Selected VMT Estimates from the 1969-70 NPTS

To estimate VMT for all or for a certain class of trips from the NPTS data, one can proceed in two ways: (1) one can add the reported lengths for all trips of this class and multiply by the sampling factor; or (2) one can classify trips according to their length, count the number in each class, extrapolate these numbers to national totals, and multiply this number by the average trip length in each class. Using the second approach, one can get some insights into the nature of possible errors.

Trip length is as reported by the driver; it is subject to substantial error, some systematic and much purely random. For the random component, the lengths of trips under 20 miles can be taken as rounding error, with lengths reported to the nearest mile. For longer trips, the rounding may be to the nearest 5 or 10 miles--the accuracy is to some extent determined by the frequency of the trip, with commuting distances more precise than the occasional pleasure excursion. Some systematic errors can be found by referring to the original, unpublished tables which were the source of the published reports.* Journeys of under 1/2 mile (5 city blocks) were recorded and treated as if they had zero length. If they are included with length one quarter of a mile, the estimated total VMT in the U.S. is increased by 0.23 percent. The distribution of reported trip length shows clearly that distances of 5 and 10 miles are preferred to distances of 4 and 9 miles respectively. When the estimated number of trips is smoothed by averaging, the total VMT estimate is decreased by 0.36 percent. Adjustment for these systematic sources of bias then leads to a reduction in the estimated total VMT of a negligible 0.13 percent. The calculations for VMT for trips to work lead to a reduction of 0.28 percent. This type of reporting preference for "round" numbers can have more serious consequences with longer trips, where one might expect the proportions of long trips to drop rapidly. In that case, the straight averaging used in the smoothing of the 4 and 5 mile count and the 9 and 10 mile counts is inappropriate and better estimates of the distribution of counts than locally flat should be used.

The major source of random error in VMT comes from the estimation of the number of trips. The sample design and estimation procedure are such that the estimated number of trips in different cells are correlated. Thus the variance

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*Unpublished Table NPT: T-5: Number of trips and vehicle miles of travel in which a single passenger car was used for the trips, classified by one-way trip length and by trip purpose. This table distinguishes eleven trip purposes and categorizes trip length into 20 groups.

of sums from different cells is not the sum of the variances. From the table "estimated standard errors for the number of vehicle trips for one day when single auto is only means" (Table IV-1 in Appendix B of NPTS Report No. 1), the structure of the standard error of a number of trips t is derived as:

$$SE(t) = 9.5 \sqrt{t + t^2 \times 6.4\ 10^{-6}}$$

where t is measured in thousands. The estimated count t in a cell can therefore be thought of as the sum of t quantities each with standard error 9.5 and the correlation between any two quantities is $6.4\ 10^{-6}$. This equicorrelation is an approximation, but is probably a good one. How is this expression for the standard error of count of trips used to derive standard errors of VMT estimates?

The approach used in the calculations for Table 3.4.2-1 is to sum the trip lengths multiplied by the number of trips with that length. But since the trip counts are imprecise and the average trip length recorded for the sample in any cell is not known perfectly, the VMT estimate here is again the true VMT with error. Now the error has three components; one is the sum of trip lengths by count errors, one is the sum of counts times length errors and the last is the sum of count errors times length errors. Assuming the length errors are mutually independent and are independent of the count errors as before, the variance of the VMT estimate now has three components, one for each of the three error components. If one assumes that thestandard errors of the reported trip lengths are 10 percent of the trip lengths, it turns out that the error components related to trip length are negligible relative to the error component due to sampling. Therefore, the variance components due to length error have been combined in Table 3.4.2-1.

Examination of Table 3.4.2-1 shows that the overall VMT estimate is quite good. The difference between the NPTS estimate and that derived from state reports is only 1.65 standard deviations. Accuracy in individual cells depends on both the number of trips and their length. Thus, for trips of 11-15 miles, there were about 17 times as many trips "home to work" as "medical or dental," and the corresponding variances are approximately similarly related. Here the average trip lengths are very close. In cells with the same counts, the standard deviations are roughly proportional to the trip lengths.

TABLE 3.4.2-2

ERRORS IN SELECTED VMT ESTIMATES
FROM THE 1969-1970 NPTS

Description of Trips	Variance Components		Standard Error of VMT Estimate	Estimated VMT (billion mi)	Relative Error (%)	Sample Size*
	Due to Sampling	Due to Trip Length**				
All Trips	1,995	1.8	44.7	776.9	5.7	34,000
Trip Purpose						
Home to work	421.0	1.07	20.5	261.5	7.8	9,600
Shopping	34.9	0.12	5.9	58.1	10.2	5,400
Medical/Dental	15.9	0.034	4.0	12.6	31.6	500
Pleasure driving	44.0	0.11	6.6	23.8	27.8	600
Shopping trip 250-499 mi	5.33	0.08	2.3	0.53	436	1
Home to work under 500 miles	147.8	0.70	12.2	5.8	210	3
Home to work, 11-15 miles	18.9	0.016	4.4	41.0	10.6	1,060
Medical/Dental, 11-15 miles	1.09	0.001	1.05	2.5	42.6	65

*The sample size given is either reported or linearly interpolated from Table NPT: T-5.

**The length errors are taken to be 0.1 times the reported length.

It is important that total VMT must be estimated from Tables with a fairly fine categorization of trip length. If the categories of trip length are broad, another variance component enters: that which is due to the distribution of trip length within each cell. This would apply, e.g., for the examples "Shopping trip 250-499 miles," and "home to work, under 500 miles." Here the error estimates given in Table 3.4.2-1 are probably too low.

3.4.3 Summary

The Nationwide Personal Transportation Study provides, in principle, most of the information needed to quantify the desired matrix. The only major exception is that it does not provide information on the type of highway used. Also, it does not provide details on driving as part of a job, and it appears not to cover joyrides which begin and end at the same address.

Mileage figures are based on subjective estimates of the respondents and thus have an unknown accuracy. Comparison of total passenger car VMT estimates within the 1969-70 NPTS, and between the NPTS and other estimates, shows discrepancies of 10 to 20 percent. Part of these discrepancies may, however, be due to errors in the other sources. As long as mileage estimates are not biased, however, their influence on overall VMT estimates appears negligible compared

with the sampling errors. We estimate that the error of the overall VMT estimate derived from the 1969-70 NPTS is about 5 to 6 percent, provided that there is no bias in the subjective mileage estimates. Errors of VMT figures for special classes of trips, corresponding to cells of the matrix, however, increase rapidly with the decreasing number of trips actually sampled in that cell, and can reach several hundred percent of the estimated VMT figure.

We expect that errors of estimates from the 1977 NPTS will be about 60 percent of those from the 1969-70 NPTS. Thus, an error of 3-4 percent for the total VMT figure appears plausible. The errors of VMT figures for the cells of the matrix, however, will still be large, though reduced.

3.5 Odometer Readings

Data Sources

Odometer readings are the only source of directly measured VMT data. Twenty-nine states plus the District of Columbia conduct a periodic Motor Vehicle Inspection Program. They are:*

1. Arkansas
2. Colorado
3. Delaware
4. Florida
5. Georgia
6. Hawaii**
7. Indiana
8. Iowa
9. Kentucky
10. Louisiana
11. Maine
12. Massachusetts
13. Mississippi
14. Missouri
15. Nebraska
16. New Hampshire
17. New Jersey
18. New York
19. North Carolina
20. Oklahoma
21. Pennsylvania
22. Rhode Island
23. South Carolina
24. South Dakota
25. Texas
26. Utah
27. Vermont
28. Virginia
29. West Virginia

plus the District of Columbia.**

Of these, four do not currently record odometer readings when the vehicles are inspected. They are:

1. District of Columbia
2. Massachusetts
3. New Hampshire
4. New Jersey.

North Carolina currently processes the odometer information to obtain annual mileage estimates. However, it appears that the following states collect sufficient information to analyze odometer readings to estimate VMT.

*Source: *Summary of State Motor Vehicle Inspection Laws and Regulations* (MVMA) [37].

**In the search to determine state practices on handling odometer data, Hawaii was not contacted.

1. Delaware. Odometer readings which are presently recorded during periodic inspections will be added in the next 4-5 months to a computer file which presently exists on registered vehicles.

2. Georgia.* The odometer readings are taken and put on forms which are saved for two years. Some information is now in the computer and they are expecting a federal grant to complete this work.

3. Louisiana. It was unclear from the initial contact how accessible the odometer reading data are; however, records are kept.

4. Mississippi. They keep inspection forms on micro-film for three years, organized by sticker number so they could be retrieved.

5. New York.* This information is presently available on a file of component failures. However, they state that comparing one year's data to another would be a difficult programming job.

6. North Carolina.* This state has been collecting both the current and previous odometer readings on the same form and analyzing these data since 1970.

7. Oklahoma.* Inspection data are recorded in computer files, and currently is being used to analyze defect rates. In the future, inspection sticker numbers will be recorded, allowing for tracing previous years' mileage. Again, it will be a relatively difficult matching job.

8. Pennsylvania. Since July 1977, data on odometer readings have been recorded and kept on hardcopy files, but it would be a major job to access them.

9. South Carolina.* Computer files are kept of inspection results, including odometer readings. Again, matching would take place.

10. South Dakota.* Vehicles involved in accidents are checked out against inspection certificates. Odometer readings are kept in the inspection file for 18 months, so matching could be done.

11. West Virginia.* This state has an interesting system which records defect repairs and charges as well as odometer readings.

The remainder of the states (15) generally required inspections and the odometer reading was recorded, but there was no centralized record-keeping performed. Generally, inspection stations, which are often state-licensed garages, keep the inspection forms.

In summary, only North Carolina used the inspection data to estimate annual vehicle travel. Several other states have the potential to do this, but there

*Most promising state programs.

would be some difficulty in performing the computer analysis. Those states which have computer records generally use them to analyze vehicle/component defect rates.

Another possible source of information on mileage is from vehicle registration files. According to data supplied by NHTSA, eight states presently list the odometer reading on the vehicle registration file. In addition, all of these states presently have automated these files. These states are:

1. Arizona	5. Mississippi
2. Florida	6. South Carolina
3. Maine	7. Virginia
4. Maryland	8. Wisconsin.

Limitations of Odometer Reading Data

Although odometer reading data would seem to have little error associated with their use, there are certain problems. First, there is the physical accuracy of the measurement. According to SAE Standard J678, odometer accuracy should be between -1 and +3.75 percent (at 45 mph). Tests of odometers at the NHTSA Engineering Test Facility in Ohio revealed that out of 17 randomly selected 1977 model vehicles, only one had an odometer which was out of the specified tolerance of plus or minus 4 percent. In addition, there are the effects of tire wear, which lead to an upwards bias in odometer readings, and there is also an effect of varying tire inflation. Since tires are more often underinflated than overinflated, this adds to the upwards bias. Second, there are data collection and processing problems. Usually it is not determined whether the odometer is in working condition or whether it has been tampered with, and both of these lead to an underestimate. Then there is the problem of the accuracy of reading the odometer and of legibility of the record. There is the "wrap-around" problem when mileage exceeds 100,000, there are problems matching one year's record with the previous year's record, and then there is the problem of vehicles moving into and out of a state.

There are basically two ways of analyzing odometer readings: (1) by matching (for the same vehicle) one year's odometer reading with the previous year's odometer reading; and (2) by determining (in each calendar year) the average odometer reading for a make/model/model year class of car and comparing it with the corresponding average from the preceding year. Negri [38] has compared these methods and concluded that the second method is easier to apply and produces relatively good estimates, except for newer model cars.

[38] Negri, *Vehicle Mileage Exposure Study*.

Overall, it appears that odometer readings can give VMT estimates with an error of roughly 5 percent, and with an upward bias of perhaps as much as 5 percent. To what extent this theoretical limit can actually be reached depends largely on the problems one encounters when retrieving and processing the original data.

3.6 Vehicle Registration Files

Vehicle registration files typically contain information on vehicle make, model, model year, body style, weight, color and sometimes engine characteristics. Sometimes such information is given only implicitly in the Vehicle Identification Number.

Vehicle registration files do not necessarily correspond to vehicles actually used. Sometimes there is a delay before a newly registered vehicle is entered in the file, and often scrapped or otherwise removed vehicles are not taken out of the file until the date for the next registration. This may lead to double registration for vehicles moved from one state to another. There is also the temporary use of vehicles with "dealer" or "repair" plates; and the use of unregistered vehicles.

Though each state has its vehicle registration file, the most convenient source of data on vehicle age, weight and geographic distribution is R.L. Polk and Company. There are two files available: (1) Auto Registration File of Existing Registrations; and (2) National Vehicle Population Profile. The registration file covered 96 million automobiles as of April 2, 1977, giving considerable detail on the vehicle, owner and geographic area (down to census tract). The vehicle profile contains information on 120 million vehicles (including light trucks) down to the county level; however, owner information is not available.

Typically, registration files do not contain information on vehicle use in terms of mileage. They may, however, provide information on private or commercial use. Nevertheless, registration files can be useful for expanding data from the NPTS or similar sources, based on a relatively small sample to national totals, to increase the accuracy of the expansion, if the sample is stratified according to factors contained in the registration files.

3.7 The Truck Inventory and Use Survey

The *Truck Inventory and Use Survey* is part of the Census of Transportation. It covers both commercial and private vehicles. The last survey was conducted in 1977, results of which are not yet available. Among information collected are:

- Make
- Model year
- Registered weight or capacity
- Annual miles during the past 12 months (if less than 12 months, estimate probable miles per year).
- Lifetime miles (odometer reading or best estimate)
- "How was the vehicle mostly used during the past 12 months (mark one box)

  ....

  For personal transportation--used in place of an automobile to go from home to work, for outdoor recreation, etc. ..."
- Gross vehicle weight
- Type of fuel: gasoline, diesel, LPG or other.

It is an important source of information because it allows separation of trucks used as personal vehicles from others. In 1972, 41 percent of all trucks were used primarily for personal transportation, and 33 percent of all truck VMT was for personal transportation.

3.8 Transportation Planning Studies and Models

Transportation planning studies collect a large amount of detailed information on motor vehicle travel, in a limited area over a limited time period. Transportation models estimate motor vehicle travel at various levels of detail from land use, population, and similar basic data, using theoretical models which were calibrated with actual data, empirical models which were estimated from empirical data (with only a rudimentary theoretical basis), or combinations of both.

Wilbur Smith and Associates found that over 100 general traffic operations studies were performed for cities from the size of Philadelphia on down, 15 TOPICS studies, and many specialized transportation studies for states, cities and regions. To illustrate the amount of information collected, we present some highlights from their study of the Boston Metropolitan Region [54] in 1965:

- Detailed travel information was collected from 48,000 households (approximately 4.5 percent of all households in the study area).
- 145,000 driver interviews were conducted. Travel information was also collected on 9,500 trucks, 370 taxis, 100,000 transit riders, and 3,800 miles of major highways and principal streets.
- The planning area was divided into 626 traffic zones.
- Trips were classified internal (start and end in Planning Area), external-local, through trips, and local-external.

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[54] Wilbur Smith and Associates, *Comprehensive Traffic and Transportation Inventory*.

- Motor vehicle trips included passenger vehicles, taxis, light trucks and heavy trucks.
- Trip purpose included: work, personal business, recreation, school, social, shopping-convenience, shopping-general, serve passengers, and change travel mode.
- Estimates of vehicle trips derived from household surveys are compared to ground counts to estimate accuracy of data.
- Data available on computer tape includes over 300,000 person trip records, 130,000 cordon trip reports, usage and performance on 4,000 highway segments, and other data.

The Georgia Department of Transportation conducted a study *A State of the Art Literature Review on Statewide Traffic Models* for FHWA in 1972 [52]. As noted above, there have been a tremendous impetus toward transportation modeling effort. The States of Iowa, Wisconsin, Missouri, Minnesota, Rhode Island, Connecticut, Michigan and Pennsylvania had completed statewide transportation studies. The States of Oklahoma, Colorado, Maryland, Kentucky, Tennessee, Wyoming, West Virginia, Delaware, North Carolina and Arkansas were in the planning or process stage. In general, these studies are oriented toward relating inter-zonal traffic (as determined by actual highway counts) to socioeconomic, demographic and other characteristics of the areas. A general conclusion is that most tripmaking could be accounted for by population and distance factors except for recreational trips where more information is needed on attractants.

Two studies prepared by COMSIS Corporation, one for NCHRP and the other for FHWA, deal with trip purpose, time and highway system from a modelling point of view [3, 53]. The major purposes of the FHWA report were:

"- to present in concise terms the techniques currently available for estimating loads on a transportation network, with reference to more detailed literature should the reader desire additional information.

- to discuss the operational decisions that must be made in applying any traffic assignment technique such as the selection of zones and network, selection of network impedance values, and the trip loading-adjustment process to be applied.

- to describe the numerous uses for the traffic assignment procedure in addition to the traditional network planning application.

- to present the evaluation of the products of the assignment process made by professional personnel and the uses to which they are put."

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[52] Arrillage, B., *A State of the Art Literature Review on Statewide Traffic Models*.

[3] COMSIS, *Quick Response Urban Travel Estimation Manual Techniques and Transferable Parameters*.

[53] COMSIS, *Traffic Assignment*.

The traffic assignment models are tied to existing highway inventories and calibrated and updated with ground counts (screen line, cordon counts, etc.). The basic data needed is origin-destination studies. There are descriptions of the UMTA Transportation Planning System (UTPS) and other less detailed models. In discussing the accuracy of collected data, the FHWA report includes the average deviations of results in traffic volume, on the order of 30 to 60 percent.

The COMSIS report for NCHRP is designed to reduce the reliance on computers for transportation system analysis. The study provides manual techniques to study: trip generation, trip distribution, mode choice, auto occupancy, time-of-day, and traffic assignment and capacity, and density. There is heavy reliance on tables, graphs and equations. Parameters are consistently reported for four urbanized area population groups: 50-100,000; 100-250,000; 250-750,000; and 750-2,000,000. The material is also disaggregated into: (1) home-based work trips, (2) home-based non-work trips, and (3) non-home-based trips.

Overall, however, one has to conclude that studies of these types present too "incoherent" information of a one-time nature to be useful for constructing a nationally representative matrix of driving under various conditions. However, it is possible that specific findings can be used to fill gaps in the more representative, but less detailed data bases.

3.9 Other Sources of Vehicle Use Information

The *National Survey of Transportation Attitudes and Behavior* [49] was conducted in 1967 and included 5000 randomly selected people, 18 years of age or older. The survey included an inventory of all trips taken during the past two days. Over 1700 cross tabulations of data are available to qualified researchers at the NCHRP offices of the Transportation Research Board. However, only a few tabulations have been analyzed and published.

Information on travel in urban areas (where over 70 percent of the U.S. population lives and more than half of all VMT are traveled) is given by the System Development Corporation in the study, *Survey of Average Driving Patterns in Six Urban Areas* [1] in which they found four distinct travel patterns (which corresponds to trip purpose):

- Two-Trip Day:
  - Home to work, work to home.

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[49] McMillan and Assael, *National Survey of Transportation Attitudes and Behavior.*

[1] Kearin, Lamoureux and Goodwin, *A Survey of Average Driving Patterns in Six Urban Areas of the United States.*

- Three-Trip Day:
  - Home to work, work to shopping, and shopping to home (closeness of shopping to home varied by region).
- Four-Trip Day:
  - Home to work, work to home, home to shopping/recreation, and return to home.
  - Home to work, work to home, and noon-time lunch (or shopping).
- Five-Trip Day:
  - Home to work, work to home, home to shopping, shopping to other shopping or recreation, return to home.
  - Home to work, work to shopping, shopping to home, then home to shopping and return.

Approximately 60 percent of the total trip days surveyed (4,702 days and 21,501 trips) were of the above types of weekday trips which are very purpose-related. This study was done in 1971 and *in the initial conception of the study, it was also intended that acceleration and deceleration distributions be examined.* However, the manual scanning and recording equipment used did not prove adequate. SDC reported that an automated scanner was being designed to process tachograph records, thus the acceleration-deceleration distributions may be retrievable. The G. M. Chase Car Study [2] seems to have solved this problem.

3.10 Summary of Information Availability

The following summary describes which information sources allow the estimation of vehicle miles of travel disaggregated according to the dimensions of the selected matrix (Section 2.6).

Trip Purpose. The only major source providing trip purpose is the NPTS. It obtains the number of trips by trip purpose (and other characteristics). There are a few important exceptions: vehicle miles traveled as part of work is only summarily obtained, without the specific trip purpose, and "joyrides" are apparently not covered by the survey. Local traffic studies may provide information on trip purpose, but their usefulness is extremely limited.

Trip Length. The only major source of trip length information is the NPTS. In addition to being a dimension of the matrix, trip length is of critical importance, because it is necessary to convert trip counts into vehicle miles of travel. Since the reported trip length is based on the respondent's subjective estimates, it is subject to random errors, and potentially biased.

Local origin-destination studies provide information on trip length, but the information is probably too isolated to be useful for quantifying the matrix.

[2] Johnson, *et al.*, "Measurement of Motor Vehicle Operation Pertinent to Fuel Economy."

Time. Time of day, day of the week, and week, month or season of the year are available in the NPTS data. They are also available for traffic counts at continuous counting stations. Time patterns of travel are relatively well known and are used by traffic engineers to estimate average traffic from short-term traffic counts.

Highway Class. The NPTS provides only very limited information on the highway used; if a trip crosses an urban/rural boundary, a trip map is made which would allow the distribution of VMT over the highway systems. Since travel time and distance are collected, average trip speed can be calculated and one can surmise on which highway system(s) the trip was made. This, however, is quite speculative.

Precise information on the highway class used is available in traffic-counting programs.

Geographic Area. As long as "large" geographic areas are considered, covering several states, the problem of assigning VMT to an area is relatively easy. If smaller areas such as a small state, a county or a city are considered, the assignment of VMT to an area may become difficult.

The original NPTS data can be disaggregated by residence of the traveler. A distribution of the VMT of long trips over the areas traversed is possible, in principle, but it is very cumbersome in practice and probably of limited reliability.

Traffic counts allow, in principle, a precise assignment of VMT even to small areas. In practice, this is limited by the spatial density of the counting stations.

VMT derived from odometer readings can be assigned to geographic areas only by making the assumption that "most" of the VMT are traveled in an area near the residence of the vehicle's owner. The larger the area, the more plausible is this assumption. The same holds true for annual VMT estimates per vehicle reported in the NPTS in the Truck Inventory and Use Survey, and for annual VMT estimates per driver collected by the NPTS.

Vehicle Class (weight). "Weight" of a vehicle is not unambiguously defined. The following are different definitions of weight.

Shipping weight is generally the average weight of the basic model within a given make/model class. This includes 4-door sedans, 2-door hardtops, etc. Options such as air conditioning, larger engines, etc. are excluded. This is the

weight generally given in the Motor Vehicle Manufacturers Association's materials, e.g., [16], *Ward's Automotive Yearbook* [44], etc. New York's (and possibly other states') motor vehicle registration file contains, however, the actual shipping weight for each vehicle, taken from the manufacturer's invoice.

Curb weight is the actual weight of a specifically equipped automobile, including a full tank of gas [43]. It is the same as "unloaded vehicle weight"[45].

Loaded vehicle weight is the curb weight plus 300 pounds [45].

Inertia weight is used by EPA for fuel economy ratings. Cars within 250 or 500 pound ranges of loaded vehicle weight are assigned a certain inertia weight.

A special problem arises with small trucks. They are commonly classified by *Gross Vehicle Weight* (GVW)--more precisely *Gross Vehicle Weight Rating* (GVWR) --which is the maximum permissible weight of the loaded vehicle. This weight differs substantially from the curb weight of the vehicle. "For example, a pickup truck with a GVWR of 5,600 pounds can weight about 3,600 pounds, almost 1,200 pounds less than a full-size sedan [46]."

To determine exact vehicle wieght, a precise identification of the vehicle by make, series, line, body style, optional equipment and model year is required. Not even from the Vehicle Identification Number (VIN) can all of this be obtained (e.g., air conditioning). However, approximate weight (and other characteristics) can be obtained from less precise vehicle identifications.

The NPTS identifies vehicles up to make, model and model year, number of cylinders, automatic transmission and air conditioning. Odometer readings on vehicle inspection records and vehicle registration files contain the VIN and, thereby, quite precise information on vehicle characteristics. Traffic counts, however, usually contain no information on vehicle characteristics. Only sophisticated counters and special classification counts provide a gross classification into passenger cars--possibly even distinguishing several classes of passenger cars--and trucks by type. This allows only very gross estimates of vehicle weight.

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[16] MVMA, *Motor Vehicle Facts and Figures '77.*

[44] Stark, *Ward's Automotive Yearbook.*

[43] Aerospace Corp., *Passenger Car Weight Trend Analysis.*

[45] USEPA, "New Motor Vehicles and New Motor Vehicle Engines -- Control of Air Pollution," *Federal Register.*

[46] USDOT, "Light Duty Truck Fuel Economy Standards," *Federal Register.*

Vehicle Model Year. The sources for model year information are the same as for vehicle class. However, traffic counts, even classification counts, do not furnish model year information.

Joint Distributions. To quantify the matrix, it is not sufficient to have VMT disaggregated by each factor representing a dimension of the matrix, but to have it disaggregated simultaneously according to all factors. The review of the information sources showed that the NPTS allows, in principle, the disaggregation of VMT according to all dimensions but highway class. Disaggregation according to highway class can be obtained from traffic count data (Figure 2.6-2). No other source provides basically different information. Therefore, with the available data, one can obtain a comprehensive matrix, if one assumes independence between highway class and trip purpose, trip length, vehicle age, and possibly vehicle weight. Such an assumption may not be quite realistic. It might be possible, by making assumptions on average trip speed by highway system, to avoid the assumption of independence between highway class and the dimensions mentioned.

Accuracy of VMT Figures

We concluded that it might be possible to estimate total annual VMT for passenger cars from existing traffic count data with a standard deviation of about 3 percent. From the 1977 NPTS data, it might be possible to estimate them with a standard deviation of about 3-4 percent. From odometer readings, one might estimate VMT with a standard error of about 5 percent, possibly biased as much as 5 percent. Combining data from all three sources, one might be able to obtain an estimate with a standard error of less than 3 percent. This, however, holds only for total VMT. The VMT in the cells of the matrix, and also in the cells of the marginal matrices will have much larger standard errors, up to several hundred percent for some driving conditions.

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4. HOW TO QUANTIFY THE MATRIX

4.1 Introduction

To quantify the vehicle use and fuel consumption matrix requires the following steps: 1) to estimate VMT for the cells of the matrix, and 2) to estimate average gals/mile for the cells of the matrix, which then allows us to estimate total fuel consumptions for each cell of the matrix. In addition to these steps, which lead to a descriptive matrix, another step is described: 3) to develop a model which allows us to study the influence of specific changes in vehicle use, and of changes of fuel consumption for certain vehicle types, or under certain driving conditions, upon total fuel consumption.

The estimates of VMT will be based on three sources: the 1977 NPTS data, data from the continuous vehicle counting programs, and on odometer readings. NPTS data will provide most of the detail of the data, but the reliability of absolute VMT in this source is likely to be limited. Vehicle count data are providing detailed information on highway use. Odometer readings provide only very aggregate data, but they are the only source of actually measured VMT data. The use of these three data bases allows some estimate of the accuracy of the final results. Another reason for using odometer data is that they, together with analyses of highway counts, can be obtained annually, whereas data of the NPTS type are collected only infrequently, perhaps once every decade. Combining current estimates from odometer readings and vehicle counts with the most recent NPTS data will result in detailed estimates with the property that, though the reliability of the detail decreases with time, the aggregate figures are as up-to-date as possible.

To estimate fuel consumption, two approaches are possible. The first is to determine for each of the cells the average values of the factors which determine fuel consumption, and estimate the resulting gals/mile of fuel consumption. This is the approach used, e.g., by Claffey. We propose to use an alternative which uses the same basic logic, but relies on aggregate relations, as derived by Herman, and does not use as detailed information as Claffey. The second approach uses a second matrix: one, whose dimensions are the key operating factors, such as average speed, temperature, etc., which directly influence fuel consumption. The VMT from each cell of the vehicle use matrix are added into the corresponding cell of the vehicle operating matrix; combining the totals with the fuel

consumption per cell gives the total fuel consumption. Both approaches are mathematically equivalent. The first approach, however, presents the information in a way which simplifies estimates of the effect of changes in vehicle use upon fuel consumption, whereas the second presentation simplifies estimates how changes in fuel consumption rates as a function of operating conditions influence total fuel consumption.

Finally, models are presented which allow us to perform these estimates. Such models are important, because it is not possible to intuitively comprehend all implications of such high-dimensional matrices. The low-dimensional matrices which can be comprehended, however, do not reveal all important aspects of the problem. These models have two levels: at the first level, they allow us to describe how fuel consumption changes when certain use factors change, assuming the fuel consumption rates as given, or how fuel consumption changes, given a use pattern, but changing the fuel consumption rates. The second level includes more basic information upon which the fuel consumption data depend, e.g. the idle fuel flow rate. With this level, one can study how changes in these parameters influence total fuel consumption.

4.2 Estimating Vehicle Miles of Travel

4.2.1 The Approach

Initially, the approach will be presented in terms of estimating the travel matrix for the entire country. Later we will discuss the modifications needed to regionally disaggregate the data.

Figure 4.2.1-1 presents an overview of the conceptual approach. It relies on three main data bases:

- Odometer data
- Continuous vehicle count data
- Data from the Nationwide Personal Transportation Study,

and on subsidiary data bases, namely:

- Vehicle registration files
- Driver registration files
- Highway inventory data, and
- Vehicle classification count data.

In addition, it is desirable to use data from the Truck Inventory and Use Survey. The main data base, providing the greatest amount of detail, is the Nationwide Personal Transportation Study, 1977. For our purposes, it provides three independent bases for estimating VMT:

- Trip information
- Driver VMT estimates
- Vehicle VMT estimates.

The first is the most detailed and, for our purposes, most useful information on motor vehicle travel. For each trip, information on its mode, which will be used to select motor vehicle trips, and on:

- Trip purpose
- Trip length
- Time when trip began (also day of week, day of month, and month of year)*
- Vehicle type (and in the case of a "household vehicle," exact identification of the vehicle).

This, using the expansion factor of the NPTS sampling plan, gives VMT travelled under conditions characterized by these factors. The greatest gap in this information is that it excludes driving done as part of a job, especially by professional drivers.

*There is also information on the duration of the trip. This information may be useful to distribute the mileage of longer trips over several hours of the day. A speculative use is to calculate the average travel speed of the entire trip, either for direct use in the matrix, or for assigning the trip to a highway class, considering other relevant factors. Our findings on average speed in Section 3.4.2 caution against such uses. An analysis of the actual data is needed before one can decide whether such uses of this information are meaningful.

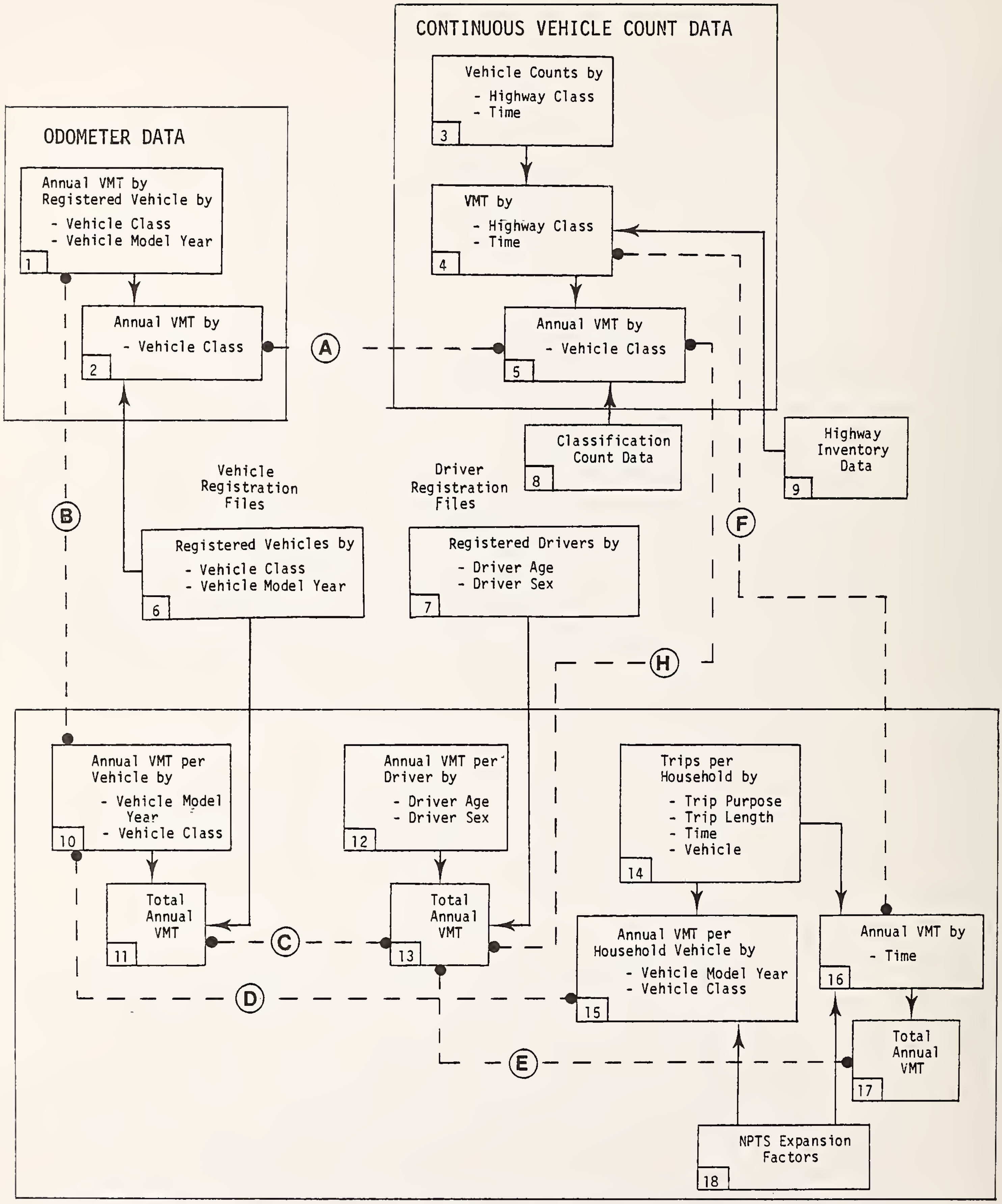

Figure 4.2.1-1. Conceptual Overview of Sources and Uses of Data to Estimate Vehicle-Miles of Travel (VMT).

Solid lines indicate sources and uses of data. Dashed lines indicate comparison of similar data, to estimate their accuracy or the effects of differences in coverage.

The second consists of drivers' estimates of their annual miles of driving. This includes all motor vehicles, also non-household vehicles. However, it appears possible to separate VMT travelled as part of one's work from other travel. Natural stratification for driver data on VMT are age and sex.

The third basis for VMT data are overall estimates of annual miles of travel for each household vehicle. These data can be easily stratified by vehicle type (and class within type), and age or model year.

The VMT estimates based on these three basically independent kinds of data can be compared in various ways to check the internal consistency of the data.

- Annual VMT per household vehicle, by class and age, can be estimated from trip data (14) and VMT for vehicle estimates (10) and compared (D).
- Total annual VMT derived from the vehicle data of household vehicles (11) can be compared (c) with total annual VMT of household vehicles derived from driver information (13). Discrepancies may also give indications on the reliability of the estimates of driving as part of a job.
- Total annual VMT from driver estimates (13), excluding driving on the job, can be compared (E) with total annual VMT derived from trip data (17).

The second data base are the continuous vehicle counts. Count data, by highway class and time of day, combined with highway inventory data, provide estimates of VMT by highway class and time. Together with data from the vehicle classification counts, annual VMT by vehicle class (5) -- possibly also by highway class -- can be estimated.

The VMT by highway class and time (4) can be compared (F) with household VMT by time (10), the differences should be travel by non-household vehicles, including buses and trucks. Also, annual VMT by vehicle class (5) can be compared (H) with annual VMT derived from driver data (13) which allow some separation of travel by vehicle class.

The third data base are odometer readings. The main purpose of using odometer readings is that they are the only direct source of actual measured mileage information. In addition, some disaggregated VMT information can be compared with corresponding information from other sources. Annual VMT by vehicle class and vehicle age (1) can be compared (B) with those derived from the vehicle information at the NPTS (10). Also, VMT by vehicle class (2) can be compared (A) with those derived from vehicle counts (5).

The Truck Inventory and Use Survey provides essentially VMT estimates also obtainable with greater reliability from odometer readings. However, it allows the identification of trucks which are primarily used for personal transportation, thereby providing additional information.

Dimensions of Matrix	Source of Information		
	NPTS	Vehicle Counts	Odometer Readings
Trip Purpose	X		
Trip Lengths	X		
Time	X	X	
Highway Class		X	
Geographical Area	X	X	X
Vehicle Age	X		X
Vehicle Class	X	(X)	X

Figure 4.2.1-2. Sources of VMT Information Disaggregated According to the Dimensions of the Matrix.

Figure 4.2.1-2 shows for which dimensions of the matrix, the three data sources can provide information. NPTS provides most of the desired information, with the exception of the breakdown by highway class.* Adding information from the vehicle counts will provide a breakdown by highway class. The addition of odometer readings does not add a new dimension. However, it allows several comparisons which can be used to check the reliability of the data from the other sources. and it is the only source which provides accurately measured VMT information. Similarly, data from the Truck Inventory and Use Survey provide no basically different information, but are another independent source.

*A rough indication of the use of different highway classes could be obtained from the information on travel within central business districts, urban areas, trip maps, and also from rough speed estimates which can be obtained from NPTS data. The results, however, are likely to be somewhat speculative.

4.2.2 Separate VMT Estimation for Each Data Source

The first step when estimating VMT for the cells of the matrix is to estimate VMT for the cells of the submatrix (marginal matrix) which can be derived from each data source.

The most extensive analyses have to be performed with the NPTS data. We assume that the data are available disaggregated by Region, and that the Census Bureau can provide tapes with original data--eliminating certain items to ensure confidentiality of the data--and the appropriate expansion factors, or, that the Census Bureau will produce the required results. In both cases, the sampling factors will also yield the sampling errors of the entries in the tables.

From the vehicle data, vehicle miles of travel for the two-dimensional matrix vehicle age--which corresponds to model year--by vehicle class will be estimated. In addition, either regional registration figures by class and age, or corresponding figures for selected states from the region--which can be considered as a convenience sample--will be used to estimate total vehicle miles of travel for the vehicle classes considered. This will be more reliable than estimating totals using the NPTS expansion factors, because the registration figures are either a complete census, or a much larger sample than the NPTS. In addition to the sampling errors, one has to study the effect of discrepancies between registration data and vehicles in use at the time the survey was taken. First, there are the differences due to the different dates, second, there are the characteristics of registration files: removed or scrapped vehicles are usually not removed until the renewal of the registration would be due, and on the other hand, it may take several weeks until newly registered vehicles are entered into the files.

From the driver data, annual VMT per driver, by age and sex can be calculated, together with their sampling variance. These data will be combined with driver registration data, either for the entire region, or for selected states, to obtain total annual VMT. Again, this will be done because errors will be smaller than if expanded from the NPTS. In addition to the sampling errors, systematic errors in the driver registration files have to be considered: a driver who moves out of state, or dies, is usually not removed from the license file until renewal of the license is due, which might be several years

hence. Similarly, newly licensed drivers may not be entered immediately into the file.

The main information source within NPTS is the trip information. From it, using the NPTS expansion factors, one can estimate VMT for the cells of the seven-dimensional matrix trip purpose X trip length X time(three dimensions)X vehicle class X vehicle age. This matrix can be collapsed to give VMT for the three-dimensional matrix time of day X day of week X season of year, and a further collapse also gives total VMT.

In addition, one can estimate from the trip data annual VMT of household vehicles by vehicle class and vehicle age, because the trip information identifies the vehicle used for a trip if it is a household vehicle.

The next data base are vehicle counts. They will be analyzed on a state-by-state basis, and the results extrapolated to the regions. The details of the analysis will depend strongly on the exact format, volume and level of details of the data. Typically, for each highway class the traffic volume by hour of day, day of week and season of the year will be estimated, together with the variation between the counting stations. Combining this with the total length of highways in each class from highway inventories gives VMT for each class, and its standard error. These data will be combined with data from classification counts which disaggregate traffic by vehicle type. Because classification counts have a smaller base than vehicle counts, the VMT figures disaggregated by vehicle type will be less reliable than figures for all vehicles combined.

The extrapolation to regions will be done on the basis of highway inventories for all states, and using traffic volume figures from nearby states.

The third data base are odometer readings. Again, they should be analyzed on a state-wide basis. Depending on the format of the basic data, two different approaches will be used. If data are available on magnetic tape, the entire data base will be used, and annual VMT figures by vehicle class and vehicle age can directly be tabulated. If the data are on hardcopy inspection forms, analyzing only a sample is more practical. In this case, one has to extrapolate from the sample, using vehicle registration information, to the entire vehicle population. Special problems which have to be addressed are vehicles which were brought into the state, vehicles which were scrapped or removed before inspection, defective or turned-back odometers, and "wrap-around."

4.2.3 Reconciling Estimates from Different Sources

Having obtained VMT estimates from each of the three sources (Figure 4.2.1-2), for the cells of the corresponding matrix, one has to combine these three matrices into a comprehensive matrix. Doing this, one faces the following problem: the NPTS matrix has a "margin" which has the same dimensions as the matrix resulting from odometer readings; and the NPTS matrix and the matrix resulting from vehicle counts have a common margin - the matrix time by geographical area. One can not expect that the VMT from the different matrices agree within the cells of the common margins. Therefore, methods to arrive at estimates for the cells of the comprehensive matrix which are compatible with the original matrices have to be found. A technique for approaching such problems was developed in the 1940s: iterative proportional fitting. The technique and many applications are described by Bishop, Fienberg and Holland [1].

IFP is essentially an iterative way of proportioning marginal totals among the cells. The iterations are around the various margins. For example, to fit a table to three given margins, one starts with the margin of Variable 1 and equally proportions out the totals among all the cells of each total's layer. Add up these adjusted entries to form a margin for Variable 2. It will usually not be the same as the given Variable 2 margin, and so one multiplies each respective layer by the appropriate proportioning constant to make Margin 2 correct. Margin 1 is now no longer correct, but one continues to Margin 3, then goes to 1 and repeats the cycle until the process converges, which is usually rapidly. IPF has "created" cell estimates with the correct margins. However, with margins coming from different sources, it is mathematically possible to have "inconsistent" marginals: the process would not converge. Appendix C presents an application of this technique.

Several statistical problems need to be addressed. First, the process uses an implicit weighting scheme for the cell entries in the marginals. This weighting scheme might not agree with the errors of the cell entries obtained from the various sources. Some work is required to modify the technique to consider this aspect.

Another point is that some cell entries of the comprehensive matrix may

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[1] Bishop, Y., S. Feinberg, and P. Holland. *Discrete Multivariate Analysis*, MIT, 1925.

have very large standard errors. If this were the case, the entries in all cells are not needed to present the information contained in the matrix. For instance, the cells of a three dimensional matrix may have very large standard errors, but the cells of the three two-dimensional marginals may have acceptable standard errors. In this case, nothing (or only little) would be lost by "smoothing"the cell numbers by calculating them from the three two-dimensional margins, which is equivalent to dropping the third order interaction terms. Tests when this can be done are also described by Bishop, Fienberg and Holland. An important practical advantage is that usually the three two-dimensional marginals contain considerably fewer cells than the complete three-dimensional matrix, which reduces the information storage. In Section 2.6, we presented an estimate that a comprehensive matrix with a reasonable level of detail would have approximately 200,000 cells. However, we expect that an analysis of the actual data will show that not all interactions up to the eighth order, which account for the large number of cells, are statistically significant. In this case, it is sufficient to store several lower dimensional matrices, from which "smoothed" entries for cells of the comprehensive matrix can be calculated, which requires considerably less storage space; how much less depends on the actual numerical dondition. We speculate, however, that it will suffice to store only a few ten thousand numbers rather than 200,000.

A second problem is that the sample may, on one or several characteristics, disagree with what is known about the population. The distribution of model year in the NPTS sample may, for example, differ from the distribution known from registration data; or the distribution of driver age and sex may differ from that in driver license files. A combination of data from these various sources may improve the reliability of the resulting estimates. Cochran, Mosteller and Tukey describe a technique that solves this problem [2]. The basic idea is the following. Assume that, e.g., g_i is the proportion of drivers of age group i in the sample, and h_i the proportion in the license file. Let x_i be the reported average annual mileage per driver in age group i. Then one can make two estimates for the annual mileage of the average driver, namely

$$\bar{x} = \Sigma g_i x_i \quad \text{and} \quad \hat{x} = \Sigma h_i x_i .$$

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[2] Cochran, W. J. Tukey and F. Mosteller, *Statistical Problems of the Kinsey Report*, Appendix C, Part V, American Statistical Assoc. Monograph, 1954.

The approach is to use a weighted mean,

$$(1 - \theta_o)\, x + \theta_o\, \hat{x}$$

as best estimates, when θ_o is determined so that the standard error of the weighted mean is minimized.

4.3 Estimating Fuel Consumption Rates

Overview

Though the purpose of this project was not to study fuel consumption to the degree vehicle travel was studied, it was necessary to review the literature on factors which influence fuel consumption, to use this information to categorize driving conditions, and finally to suggest how one could estimate fuel consumption under various driving conditions. We have concluded that information to estimate fuel consumption with the same level of accuracy as one could estimate vehicle travel for specific driving conditions is not available. There is no program which collects information on fuel consumption to the extent or level of detail of the Nationwide Personal Transportation Study or the traffic counting programs. The Environmental Protection Agency, in cooperation with the Department of Energy, conducts an annual certification program which tests individual makes and models for fuel economy and emissions under simulated driving conditions--both city and highway. The EPA fuel economy estimates have been criticized for many reasons: prototype models are tested, driving cycles are not representative, etc. EPA fuel economy estimates are not often achieved under real-world conditions. Currently, revisions are being considered. One suggestion is to provide only relative rankings among vehicles. Automobile manufacturers have developed models of vehicle performance in order to simulate fuel consumption under different driving conditions. However, these efforts have not included the transient effects of temperature, which have been studied at government research facilities with engines on test beds. On the other hand, some researchers - both government sponsored and industry - have focussed on actual performance of specific vehicles on the road. Empirical relations have been derived for the influence of one or two factors (grade, speed, etc.) on fuel consumption. The key problem is the combination of this disjointed body of information. The objective is to estimate the influence of the following factors (both individually and in combination) on fuel consumption:

- Average speed
- Trip length
- Temperature
- Vehicle class
- Vehcile model year.

Discussion of Factors

Average Speed. Work done at General Motors Research Laboratories points out the very strong relation between average trip speed and fuel consumption

under urban driving conditions [3]. Average trip time per unit distance (the inverse of average trip speed) explained 71.4 percent of the variance in the fuel consumption for urban driving conditions - definitely for speeds up to 40 mph and possibly for speeds up to 50 mph. This strong linear relationship (as average speed increased, fuel consumption per unit distance decreased) is based on some restricting conditions: tests were done with a fully warmed up vehicle over fairly flat terrain. This relationship will not hold as the average trip speed increases and the effects of aerodynamic drat become more important. At higher speeds, fuel consumption per unit distance will no longer decrease but will start to increase. The apparent paradox that at low speeds fuel consumption decreases with average trip speed is due to the fact that in actual driving, low trip speeds are due to frequents stops and slowdowns.

Though the linear relation has been derived only for urban driving, it appears plausible to use it also as a first approximation for rural driving.

Trip Length. Many vehicle tests are conducted on fully warmed up automobiles. However, the fact is that most trips are of such a short distance (less than 10 miles) that vehicles barely have a chance to become fully warmed up. The relative cold start fuel economy (versus fully warmed up fuel economy) climbs from about 50 to 90 percent as trip length increases from one to ten miles [4,5]. We have previously pointed out (see discussion of NPTS data in Section 3) that there seem to be distinctly different average speeds for trips of one to two miles versus three to ten miles. The combination of these factors must be considered when estimating fuel consumption rates for different driving conditions.

Temperature. Temperature interacts with trip length. When the ambient temperature is 10°F rather than 70°F, the average fuel economy versus trip length graph is ten to twenty percentage points lower. Eccleston and Hurn at the Bartlesville Energy Research Center have done similar work on ambient temperature and fuel consumption (and vehicle emissions)[6]. Graphs of the Bartlesville data do not show the smooth asymptotic relation presented in the earlier study, and the data show a considerably greater fuel economy penalty for low temperatures. This type of data should be further analyzed to identify sources of discrepancies.

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[3] Evans, Herman and Lam, *Gasoline Consumption in Urban Traffic.*
[4] Scheffler and Niepoth, *Customer Fuel Economy Estimated from Engineering Tests.*
[5] SAE Fuel Economy Measurement Procedures Task Force.
[6] Eccleston and Hurn, *Ambient Temperature and Vehicle Emissions.*

Vehicle Weight is very strongly related to fuel economy. The general formula given in the literature is that a 10 percent change in weight results in a 5 percent change in fuel economy [7,8]. However, this result is generally obtained by comparing different vehicles, not the same vehicle with different loads. The engine size and transmission ratios are generally fitted to the vehicle size to achieve certain performance levels. Therefore, vehicle weight is not only directly affecting fuel economy but, importantly, is also related to many other vehicle characteristics (such as engine and transmission) which influence fuel consumption.

There are limits to the levels of accuracy with which one can estimate "average" vehicle fuel economy in any vehicle class. The first limitation is introduced simply by testing limitations. Section 3 describes the CEM analysis of EPA data showing an average standard error of 2 to 6 percent. Secondly, there are errors introduced when one aggregates vehicles into categories. Austin and Hellman show the effect of this aggregation into inertia weight classes [8]. The standard errors of the fuel economy estimates averaged around 15 percent. This error could be reduced by computing a sales-weighted average fuel economy economy estimate for each category. Finally, there is the error in the "average" estimate one is using. The question is what that average really reflects--the estimates derived from the EPA driving cycles are admittedly non-representative.

Vehicle Model Year. Age *per se* does not seem to worsen fuel economy in any uniform manner. Claffey does state that fuel consumption rates increase slightly (5 to 6 percent) after a vehicle is four years old and has more than 60,000 miles of travel [9]. Between model years, however, there have been changes from year to year within each weight class and often inconsistent changes between weight classes. For instance, in 1974, some classes improved while others did not.

The five factors seem to have the strongest influence on fuel consumption rates as far as driving conditions are concerned. Most vehicle factors which have a direct and significant influence are ignored,for instance, engine size, transmission type and gear ratios, etc. They are essentially averaged out within each vehicle class.

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[7] Huebner and Gasser, *Energy and the Automobile--General Factors Affecting Vehicle Fuel Consumption.*

[8] Austin and Hellman, *Passenger Car Fuel Economy--Trends and Influencing Factors.*

[9] Claffey, *Running Costs of Motor Vehicles as Affected by Road Design and Traffic.*

Suggested Approaches

One approach for estimating fuel consumption rates for the various cells of the driving condition matrix relies largely on empirical relationships derived from testing and experimentation. The basic steps to estimating the fuel consumption rates are:

1. Develop a set of correction factors for temperature and trip length based on the results of the work of Scheffler and Niepoth at GM [4] and of Marshall *et al.* at the Bartlesville Energy Research Center [10]. The correction factors would increase the basic fuel consumption rate above the fully warmed up, 70° fuel consumption rate for the selected temperature and trip length categories.

2. Use the equations developed by Evans, *et al.* at GM to construct correction factors which results average speed fuel consumption to the basic fuel consumption rate. The GM material will possibly need modification at higher average speeds because of influences of aerodynamic drag.

3. Use the EPA Buyers' Guide Data and similar material [8] to construct basic fuel consumption rate for the selected vehicle weight and age categories. The fuel consumption rates calculated for the city and highway driving cycles will have to be modified to make them more representative of on-the-road performance.

The distribution of the fuel consumption rate data over all of the cells of the matrix depends on the interactions between the fuel consumption rate and these factors. For instance, since average speed varies with highway class and time, one will find different fuel consumption rates for the combinations of these two factors. Similarly for other factors like time and geographic area, etc. However, different trip purposes will not have different fuel consumption rates. The different (total) fuel consumption related to trip purpose will be determined by the distribution of VMT by trip purpose, time, highway class, trip length, etc.

Another possible use of the EPA data would be to take the fuel economy estimates and average speeds represented by the EPA cycles (the average highway speed is about 50 mph and the average city speed about 15) based on the linear relationship established by Evans, Herman, *et al.*, one could analyze the effect of different vehicle factors (engine size, transmission, etc.) on consumption rates.

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[10] Marshall, "Automotive Power Plant Evaluation."

4.4 Developing a Fuel Consumption Model

The purpose of the fuel consumption model is to organize information contained in the driving condition matrix with regard to VMT and fuel consumption rates so that pertinent questions can be answered, e.g., what would be the effect on fuel consumption if commuter travel were reduced two percent (by which means that reduction would be achieved is irrelevant for the application of the model). It is not an economic model which could estimate the reduction in FMT (in any category), given increases in the cost of gasoline, motor vehicles, parking, etc. This effect would have to be determined externally.

Given the number of factors concerned, and number of categories for each factor, this model can only be considered in terms of a computerized system. The distribution of VMT by driving conditions can be thought of as a nine-dimensional matrix which is made up of an eight-dimensional matrix and a five-dimensional matrix which overlap along four dimensions. The eight-dimensional matrix is based on the Nationwide Personal Transportation Study and the five-dimensional one on traffic counting programs. As discussed in Section 4.2.3, we expect that the analysis of actual data will result in further simplification of the structure of the matrix. The distribution of fuel consumption rates by driving conditions is based on functional relationships derived from empirical data. These numbers do not reflect the occurrence of driving by these conditions (presumably there is no sub-zero driving in Florida or Southern California). The numbers reflect what the fuel consumption rate would be for these conditions if they occurred. Total fuel consumption would be the sum, over the entire matrix, of the products of the fuel consumption rate and VMT estimates in each cell.

Some of the uses of a model which incorporated this information could be:

- To determine which factor (affecting VMT on the fuel consumption rate) would have the greatest effect on total fuel consumption.
- To test the effect of modifying certain factors (affecting VMT or the fuel consumption rate) on total fuel consumption.
- To estimate the changes required under driving conditions (VMT and/or the fuel consumption rate) to achieve reductions in total fuel consumption.

Before applying this model to these uses, one would want to test out the model. A basic test would seem to be to compare total fuel consumed in an area (state, region, total U.S.) to the amount estimated by the model. However, the model only applies to personal use vehicle travel and therefore should understate total fuel consumption. The smaller the region for testing, the greater the degree of

potential errors due to fuel inventory carryovers and out of region (state) fuel purchasing, etc. The model should be tested for its sensitivity to seasonal variation vehicle mix, highway speed changes, fuel consumption rates, etc.

The structure of the model can not be rigidly prescribed; however, one can say that there are two basic factors to be considered--the mathematical nature and the computer framework. The basic mathematical structure is simple: the model is a sum of VMT times the corresponding fuel consumption rate over all cells. However, the factors defining the cells do not directly determine the fuel consumption rate; rather, it is determined by the intermediate factors: model year, vehicle class, temperature, trip length, and average speed. Therefore, one has two alternative structures for the model. One is to calculate for each of the cells of the matrix average values of the five factors, and determine the corresponding fuel consumption. The other is to aggregate the VMT from the cells of the nine-dimensional matrix into cells of a five-dimensional matrix defined by the factors determining fuel consumption. Both approaches are equivalent, but one may be more convenient for the study of certain problems than the other.

The computer framework is important for two reasons. One is the large amount of information to be stored and processed each time an analysis is made--possibly several million cells, though a thorough analysis and realistic simplification of the data is likely to result in only several ten thousand cells. The other is that the model should be able to answer a wide range of questions. These questions may deal with fuel consumption under certain conditions, making certain assumptions, but they may also "simply" deal with displaying the entries in certain cells or certain low (1, 2, or at the most 3) dimensional marginal matrices. The latter capability is important, because there is no other practical way of displaying the information in the matrix. Illustrative examples of constructing and using a scaled down matrix is presented in Appendices C and D.

The amount of information in the VMT matrix could be close to exceeding the quickly accessed storage capacity of any but the largest computer systems. High density magnetic tape could contain the information; however, the processing of the tapes could be slow and expensive because of reading speed. If tape is chosen as the mode for storage of the full driving condition matrix, then the programs to access that data should be efficient in data input and output, e.g., PL/1 rather than FORTRAN. It might also be feasible to construct subfiles of the overall matrix by collapsing information along selected dimensions. Building a library of such subfiles in the initial steps might increase the accuracy and reduce the cost of running the model.

4.5 References for Section 4

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5. RESEARCH PLAN FOR PHASE II

5.1 Overview

This study was conducted as the first phase of a two phase project on vehicle travel and fuel consumption. In this first phase we have categorized driving conditions, identified and evaluated potential sources of information on vehicle travel and fuel consumption, and developed methods for using the available information to estimate travel and fuel consumption under the specified driving conditions. The final task of this phase is to formalize a plan for the application of the knowledge accumulated in the first phase, which describes how to construct an operational model of vehicle travel and fuel consumption. The construction of this model would be the objective of Phase II.

The purpose of the model is not only to "hold" the data on vehicle travel and fuel consumption under different driving conditions, but also to be able to provide answers to certain questions, such as how much fuel is consumed in commuter trips, etc. This latter objective introduces additional requirements on the computer structure of the model.

Phase II can be organized into the following five tasks:

- Task 1: Review and Selection of Data Sources
- Task 2: Basic Data Collection and Processing
- Task 3: Vehicle Miles of Travel Estimation
- Task 4: Fuel Consumption Rate Estimation
- Task 5: Model Development.

We estimate that the minimal effort to produce meaningful results would be 1.5 person years. A more extensive effort could go to a somewhat finer level of detail, and/or utilize a more extensive data base. We estimate, however, that increasing the level of effort above four person years would not improve the results noticeably. If the level of effort was increased much above this, special original data collection rather than the use of available data could become worthwhile.

A period of one year would suffice to perform the study. A shorter period, even at the minimal level of effort, may lead to inefficiencies. Similarly, at higher levels of effort, extending the period may allow more efficient scheduling of the work, especially the data collection efforts.

5.2 Research Plan

In this section we outline the basic contents of each of the Tasks listed above.

Task 1: Review and Selection of Data Sources

The basic data sources which have been identified as having information on travel are:

- Nationwide Personal Transportation Study (definitely)
- Vehicle Count data from selected states (also essential)
- Odometer reading data from selected states (highly desirable).

The Nationwide Personal Transportation Study would have to be reviewed in terms of:

- Sampling scheme
- Expansion procedures
- Overall methodology.

Several states would have to be selected for their vehicle count data. The criteria for selection would be: (1) quality of the vehicle counting program; and (2) geographical representativeness. At least five states, but probably not more than 20 are needed. It would also be most desirable to have these states match states with odometer reading data. The following states seem to be the most likely candidates for selection:

1. California (very large state, good counting program, no odometer data);
2. Georgia or North Carolina (good for traffic counting and odometer data);
3. New York and Wisconsin (larger states, odometer data, Wisconsin has good counting program);
4. For geographic distribution:
   a. Texas
   b. Oregon or Washington
   c. Kentucky or West Virginia
   d. Colorado, Montana, Idaho, or Wyoming.

In each of the above states one would review in detail the data collection plans, procedures, and expansion methods. Because of the "individuality" of each state's methodlogy, this task is not a simple review of manuals or other literature. This task will require a step-by-step description and identification of the traffic counting system and potential sources of error. In addition to this detailed review of state vehicle counting programs, one should review the state highway inventory data, vehicle registration files, driver registration files and

odometer reading data (if available). R. L. Polk should also be contacted at this time to determine the detail and cost of obtaining nationally representative vehicle registration data.

Based on the information derived so far, the final subtask of Task 1 would be to develop a detailed work plan for the remaining tasks and subtasks. This would include the data collection and processing plan, and procedures for expanding data samples to regional and national totals.

Task 2: Basic Data Collection and Processing

Nationwide Personal Transportation Study: Either obtain NPTS data or work with the Bureau of the Census to develop national and regional estimates of the desired matrix (vehicle x trip purpose x time x trip length x geographic area) and possibly other tabulations, e.g., according to driver characteristics, etc. Because of the confidentiality of some data, it may not be possible to have direct control over the basic NPTS data. If the Bureau of the Census or Federal Highway Administration produces the desired tables, they would also have to determine the accuracy of the estimates.

Vehicle Count Data from Selected States: From the selected state highway departments, vehicle count data tapes and/or suitable summaries will be collected. Highway inventories or other such information will be needed to determine the location of counters by road system and also the amount of roadway in each system. Another type of highway department data needed is vehicle classification data. From the Federal Highway Administration, corollary data will be obtained (on all states) including continuous counting program data and vehicle classification data.

Odometer Readings: Collect samples of odometer reading data (if only available on hardcopy). Otherwise, obtain computer tapes with odometer reading data (whether from inspection or registration files). Also obtain vehicle registration data, in order to adjust estimates of annual vehicle miles of travel, based on odometer reading alone. Calculate regional and national estimates of VMT by vehicle age and class.

Driver Registration Data: These data are needed to expand results derived from NPTS. The sources of this information can be either the selected states or FHWA.

R.L. Polk Data: Obtain a nationally representative sample of registered vehicles by vehicle age and class for national and regional estimates.

Truck Inventory and Use Survey: If this data base is to be used, either "sanitized" data tapes have to be obtained from the Census Bureau, or requirements developed for tabulations to be produced by the Census Bureau.

In all cases, it is necessary to make estimates of the accuracy of the data due to sampling schemes, expansion factors, aggregation, etc.-where this is possible.

Task 3: Vehicle Miles of Travel Estimation

The basic objective of this task is to develop estimates of the miles traveled under various driving conditions and to estimate the accuracy of those estimates. The procedure to be followed in achieving this objective is described in Section 4 of this report. Basically, the procedure is to use the data bases (obtained and prepared in Task 2) to make several estimates of VMT (aggregate and subcategories) and to compare these estimates, attempting to explain the discrepancies. Specifically, one should develop the estimation procedure described in Section 4 in detail, considering the exact scope and reliability of the data collected, and modifying the procedure where necessary or advisable. Then the researcher should apply the estimation procedure to obtain VMT values for all the cells of the matrix and also the associated error estimates. At this point, one should produce some interim results showing important aspects of the VMT matrix, with tabulations, graphs, or by other means.

Task 4: Fuel Consumption Rate Estimation

The objective of this task is to produce fuel consumption rate estimates (gallons per mile) for each of the cells of the matrix developed in Task 3. In order to achieve this objective, one should build upon the material presented in Sections 2 and 4 of this report. Specifically, the literature review performed in this study should be updated, focusing on the influence of:

- Average trip speed
- Trip length
- Temperature
- Vehicle weight (class)
- Vehicle model year.

The review would aim at reconciling and combining the information from the various sources. The ultimate objective of the task would be to develop estimates (with estimates of their accuracy) of fuel consumption rates for all of the above factors and then extrapolate that to the full matrix.

One should also investigate the feasibility of expanding the estimation procedure to focus on more detailed vehicle factors which influence fuel consumption, e.g., idle fuel flow rate, transmission type, etc.

Task 5: Model Development

The objective of this task is to develop a model of personal travel and fuel consumption in motor vehicles. The model will have a mathematical structure and will be manipulated within a computer framework.

Two versions of the model are to be developed:

1. Let i indicate the cells of the matrix and x_i the VMT and a_i the fuel consumption rate of the corresponding cell i.

   Then the total fuel consumption equals:

$$F = \sum_i x_i a_i$$

2. Let j be the cells of a matrix with the five factors listed in Table 4 as dimensions, and a_j the fuel consumption rate in each cell j. Let $i \varepsilon I_j$ be those cells of the driving condition matrix whose fuel consumption factors correspond to j. Then the total fuel consumption is:

$$F = \sum_j \left(\sum_{i \varepsilon I_j} x_i \right) a_j$$

Both models give numerically the same result, but they allow presentation of different intermediate values. The model should be programmed so that driving done (and fuel consumed) under specific driving conditions can be calculated and presented. For example, how many miles are driven and how much fuel is consumed on home-to-work trips, for the various categories of trip length. How many miles are driven and how much fuel is consumed under different temperatures, how many miles are driven and how much fuel is consumed by travel in various speed ranges, on various highway classes, etc. The mathematical models in themselves are simple. What is not simple is to develop a logical structure which allows one to pose questions and get answers to the above. (A further desirable feature would be the ability to easily modify cell values to determine the effect of modifications in travel or fuel consumption rates.)

If the refined fuel consumption model of Task 4 has been developed, then the mathematical model has to be expanded by making the a_i functions of the various vehicle parameters t_k such that $a_i(t_1,\ldots,t_k)$. Consequently, the mathematical model has to incorporate questions on how a change in any one of these vehicle parameters influences total fuel consumption.

5.3 Scope of Phase II

The following estimates of time and levels of effort required for each task are based on our experience with - to varying degrees - similar studies. Because this experience is not directly applicable, and because there is considerable leeway in the level of detail to which, and the thoroughness with which the various activities can be performed, these estimates are not very firm, as indicated by the ranges.

Task 1: Review and Select Data Sources.

We estimate that 5-9 person-months are required, primarily dependent on the number of states to be used as data base. Required experience is primarily in systems analysis, and to some extent in statistics. A period of 2-3 months will be sufficient.

Task 2: Basic Data Collection and Processing

We estimate that 5-11 person-months are required, depending on the detailed nature of the data which the Census Bureau can provide, and on the number of states in the data base. Two to five calendar months may be required. Required is experience in statistics, data processing, and to a lesser extent, in systems analysis.

Task 3: Vehicle Miles of Travel Estimation

The scope of this task is largely independent of the extent of the data base. Three to four person-months will be required. One and a half to two calendar months will suffice. The required experience is primarily a thorough familiarity with the overall approach, the nature of the data bases, their strengths, weaknesses and discrepancies, a broad knowledge of potentially useful statistical techniques, and the capability to select the appropriate one in consideration of the characteristics of the various data bases.

Task 4: Fuel Consumption Rate Estimation

We estimate that 3-8 person months are needed, depending on the degree of detail desired. One and a half to six calendar months may be needed. The primary qualification is in systems analysis and a full understanding of the design and use of this matrix and the model. Source expertise in automotive engineering is needed.

If it was desired to refine the fuel consumption rate estimates to determine their dependence on specific vehicle and engine design parameters, considerable (6-11 person-months) additional effort would be required. Much of this would require experience in automotive engineering.

Task 5: Model Development

We estimate that 2-4 person-months will be required over a period of 1-2 calendar months. Because the models are mathematically simple, the emphasis has to be on computer programming skills: to develop programs which allow to ask avid range of questions and are still simple to use, and which produce outputs in a clear and easily comprehensible format.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Many factors are known to influence directly or indirectly the fuel consumption of motor vehicles. Their influences differ greatly in magnitude, and they differ in their nature and in the context in which they operate. A framework containing "all" factors would be very large, practically impossible to quantify, and too cumbersome to use. To make it practical, a limited list of factors has to be selected. Even with the factors selected in this study, the framework remains extensive, and it is not easy to quantify.

Currently available figures on vehicle miles travelled are of limited accuracy, and of a limited level of detail, which is not sufficient to quantify the matrix selected.

However, there are sufficient original data available, namely in the 1977 NPTS, the state continuous vehicle counting programs, and the records of various states'motor vehicle inspections, to allow estimating VMT within the cells of the matrix. With the exception of the NPTS, the data are continuously generated, and can be used to maintain the matrix up-to-date. Certain details of the structures, however, will become less reliable over time, as the detailed vehicle use pattern start to deviate from those existing in 1977.

On automobile fuel consumption, a large body of knowledge exists. Most of it is, however, unrelated; the results of studies dealing with different aspects of the problem can rarely be combined to find the joint influence of several factors. Therefore, fuel consumption for the cells of the matrix can be estimated only with limited reliability.

6.2 Recommendations

An obvious recommendation is to perform the second phase of this study, because we found that the objectives can largely be achieved with available basic data.

Some of the basic data, the continuous vehicle count data, and odometer readings, are collected on an on-going basis. We recommend that standard procedures be developed, to process and analyze these data to obtain better vehicle miles of travel information than currently available which is based on widely differing estimation procedures, and also utilize fuel consumption, which appears an unreliable indicator of VMT.

We recommend that efforts of agencies collecting VMT information be coordinated with NHTSA's efforts to collect "exposure" information. Most likely their exposure will be VMT, categorized according to criteria relevant for motor vehicle accident studies.

We recommend to explore the feasibility and practicality of automatic driving recorders. Such recorders should be simply installable in automobiles, and record over time, acceleration, deceleration and speed, miles travelled, temperature, and possibly also calculate RPM and torque. Such recorders could be placed for short periods (a few days) into a sample of vehicles. The results would give additional information of driving conditions, and could be used to monitor existing driving cycles, or to design more realistic driving cycles for fuel consumption studies.

We recommend that fuel consumption studies of the type conducted by the GM Research Laboratories be continued and expanded. They should cover a wider speed range, and also a wider range of driving conditions, rural roads or hilly terrain.

As a second step, the dependence of the parameters of such global models as developed by GM on specific vehicle characteristics should be developed.

In addition to current studies of fuel consumption which typically concentrate on one factor, keeping others constant, the interactions between the various factors should be studied, and mathematical models developed which approximate complex interactions. Such models are needed to better predict how changes in driving conditions affect fuel consumption.

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APPENDIX B: FACTORS INFLUENCING FUEL CONSUMPTION

The primary purpose of this study was not to perform an exhaustive or critical review of the literature on fuel economy. The primary objective was to organize driving situations into categories which represent the various driving conditions, and to determine how to estimate the absolute and/or relative amount of fuel used under these conditions. The first task, therefore, was to determine appropriate categories of driving conditions. In order to do that, CEM reviewed the literature to determine which factors influence fuel consumption (directly and indirectly) and how well these influences are quantified. In this way, we hoped to learn what was known about travel characteristics and highway use, in relation to each other and to fuel consumption. The review of the literature took place in an iterative fashion. Material at hand, material suggested by the technical monitor and new material which seemed directly relevant was quickly collected and reviewed in light of the initial task (categorization of driving conditions) described in the FPR and study proposal. This initial review broadened the list of initial factors and also clarified the importance of indirect, as well as direct, influences of factors on fuel consumption. In order to assess the information on various driving factors, an expanded list of factors was compiled and relevant material reviewed again in more detail. At this point, pertinent facts were extracted from individual sources. These individual items of information were collected by factor and presented in an interim report. The basic purpose of this material was to provide background information for the categorization of driving conditions. Although our purpose was not to critically review this literature, it is obvious by the juxtaposition of information from various sources of the magnitude and range of effects one can expect. *The range of reported effects and the often limited and artificial conditions of the tests illustrates the low reliability of any specific reported effect.* Given that general but extremely important caveat, we include these brief extracts of information. The factors included are:

1. Air Conditioning
2. Temperature
3. Wind/Aerodynamic Drag
4. Air Pressure
5. Slowdowns (per mile)
6. Stope (per mile)
7. Average Speed
8. Traffic Volume
9. Attempted or Design Speed
10. Trip Length
11. Grades
12. Geographic Area
13. Highway System
14. Curvature
15. Highway Surface
16. Vehicle Characteristics.

FACTOR #1 AIR CONDITIONING

Claffey, FHWA, 1972 From Posey, K., Memorandum	10% increase in gpm	a/c clutch engaged/disengaged Vehicle Normal operating conditions 80°F	
Cornell, 1965 In MVMA, 1973 (Also in Automotive Fuel Economy, 1975)	2.5 mpg loss at 20 mph to 0.5 mpg at 80 mph	85°F	Assuming 16.7 mpg rating for the driving cycle results in a 15% increase in gpm. The results for the 70 mph road test show a 6.4% increase in fuel consumption. More recent models have greater percentage penalty because of lower mpg.
Heubner & Gasser, 1973 In Austin & Hellman, 1973	13% decrease in mpg	Urban driving cycle (85°F)	
EPA, 1972 In Austin & Hellman, 1973	9% decrease in mpg	Urban driving cycle (70°F)	
Eccleston & Hurn, EPA, 1974	11% decrease in mpg		
Coon & Wood, 1974 In Automotive Fuel Economy, 1975	a/c penalty varies between 1 and 5 mpg (~20%) in a similar fashion depending on vehicle speed. Difference is small at 20 mph, large at 30 mph, and then gradually smaller up to 70 mph.		This is equivalent to a 16.6% increase in gpm at 30 mph, and 5.9% at 70 mph.

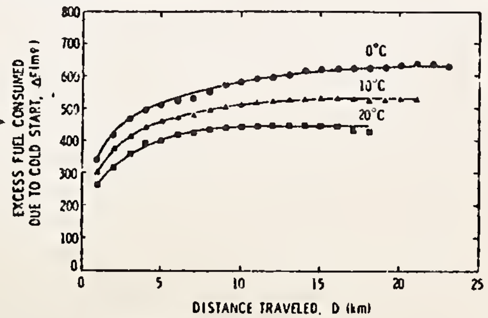
FACTOR #2 FUEL TEMPERATURE/AMBIENT TEMPERATURE

Scheffler & Niepoth, 1975
In Austin & Hellman, 1973

- 6% mpg loss 10°F vs. 70°F
- Warm-up penalty 25%-30% depending on trip length

Chang, Evans, Herman, etc., 1976

- Excess fuel consumed due to cold start



FACTOR #2 FUEL TEMPERATURE/AMBIENT TEMPERATURE (Continued)

Eccleston & Hurn, EPA, 1974	• 10% mpg loss 75°F vs. 20°F		
Schultz, et al., 1976	• 4 lbs/hr idling fuel consumption rate (75°F) • 10 lbs/hr idling fuel consumption rate (25°F)		Diesel does not have cold weather penalty.
SAE Fuel Economy Task Force, 1975 In Automotive Fuel Economy, 1975	• Δ 30°F winter average = 33°F summer average = 63°F	Δ 4% fleet mpg	
Claffey, NCHRP Rpt. 111, 1971 From Posey, K., Memorandum	• gpm increases 0.001 gpm for each 10°F drop at all speeds (~ 2%)	Uniform speed Air temperature Level Straight Dry asphalt Calm wind 4000-lb Chevrolet	
EPA, 1976	• 11% mpg loss (50°F) • 15% mpg loss (20°F)	50 mph cruising	

FACTOR #3 WIND/AIR RESISTANCE

Source	Finding	Conditions
WIND		
Cornell, 1965 In MVMA, 1973	• 18 mph headwind causes 2.3 mpg loss (16.5%) • gpm increases from 0.0719 to 0.086 (19.6%)	Full size car 70 mph
EPA, 1976	• 18 mph tailwind → 19% mpg gain 18 mph crosswind → 2% mpg loss 18 mph headwind → 17% mpg loss	50 mph cruising speed 50 mph cruising speed 50 mph cruising speed
AERODYNAMIC DRAG		
EPA, 1976	• Most significant size factor is frontal area--not directly proportional to weight • 1930's drag coefficient = 0.70, today's less than 0.50	
Heubner & Gasser, 1973 In Austin & Hellman, 1973	• 10% decrease in drag causes 4.2% mpg increase	70 mph cruising
Marks & Niepoth, 1975	• Sensitivity of fuel consumption to the product of frontal area and drag coefficient (gallons/100 miles vs. C_d x Area):	Values now determined using simulation modeling. Obviously higher speeds have greater effect.

Sensitivity	Test Cycle
0.024	SAE-URB
0.058	EPA-URB
0.095	EPA-55/45
0.048	GM-CTY/SUB
0.140	EPA-HWY

FACTOR #3 WIND/AIR RESISTANCE (Continued)		
Cornell, 1965 In MVMA, 1973	• Road load horsepower = $K_1WV + K_2DAeV^3$ where K_1 and K_2 are constants W is car weight V is car speed D is vehicle drag coefficient A is frontal area of the car e is air density	• For most passenger cars, D varies between 0.4 and 0.6. • At 20 mph, rolling resistance horsepower ~ 4 hp, and air resistance negligible. At 80 mph, rolling resistance is 20 hp, air resistance about 40 hp.
Huebner & Gasser, 1973 In MVMA, 1973	• 10% reduction in air and rolling resistance increases mpg 0.2 to 0.7, depending on driving condition.	

FACTOR #4 AIR PRESSURE/ELEVATION		
Claffey, NCHRP Report 111, 1971 From Posey, K., Memorandum	• No effect below 2000 feet • Small effect at 3000 feet • 20% increase in gpm for 10% grade as altitude increases from 3000 to 4000 feet	Uniform speed Straight Good surface Calm wind 80°F 4000-lb Chevrolet

FACTOR #5 SLOWDOWNS PER MILE

Claffey, NCHRP Report 111, 1971[1]
Claffey, FHWA, 1976[2]
Winfrey, 1969[3]
Claffey, HRB Bulletin 276, 1960[4]
from Posey, K., Memorandum[4]

- Excess fuel for 10 mph slowdown and acceleration back to speed (4000-4500 lb vehicle):

Speed	Ref 1	Ref 2	Ref 3	Ref 4
30 mph	0.004	0.007	0.003	0.003
40 mph	0.004	0.006	0.005	0.004
50 mph	0.004	0.005	0.006	0.006

- 30 mph slowdown from 50 mph excess fuel consumption is 0.01 gals.
- Excess fuel consumption independent of acceleration/deceleration rates.

Planning Environment International, 1977

Acceleration Rates (mph/sec) Following Slowdown

Speed Difference from Condition Preceding Curve (mph)	Open & Unrestricted View After Curve Start Speed (mph)			Intermediate View After Curve Start Speed (mph)			Restricted View After Curve Start Speed (mph)		
	40	50	60	40	50	60	40	50	60
Less than 10 mph	0.72	0.60	0.52	0.48	0.40	0.34	0.12	0.10	0.09
10-20 mph	0.96	0.80	0.69	0.72	0.60	0.52	0.36	0.30	0.26
More than 20 mph	1.08	0.90	0.77	0.84	0.70	0.60	0.48	0.40	0.34

Speed difference induced by curve can be calculated, see curvature.

FACTOR #5 SLOWDOWNS PER MILE (Continued)

Planning Environment International, 1977

Speed Transition Probability Matrices for between Interchange and within Interchange areas on expressway given various levels of V/C and distance between interchanges based on collected data--

Example of matrix:

Initial Speed \ Final Speed	30	35	40	45	50	55
30	.40	.30	.20	.10	0.00	0.00
35	.20	.35	.20	.15	0.05	0.05
40	.05	.10	.45	.15	0.15	0.10
45	.05	.10	.15	.42	0.18	0.10
50	.00	.05	.10	.16	0.54	0.15
55	.05	.05	.10	.12	0.20	0.48

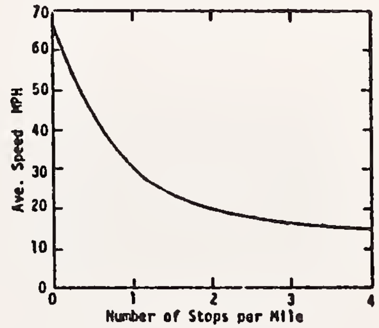
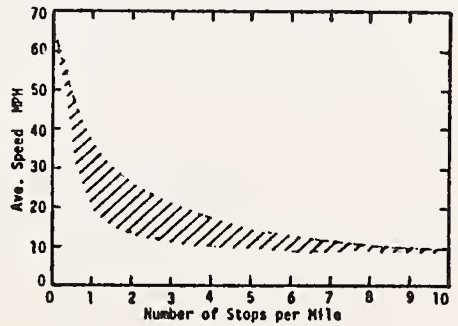
Probability of maintaining same speed is high.

Claffey, NCHRP Report 111, 1971

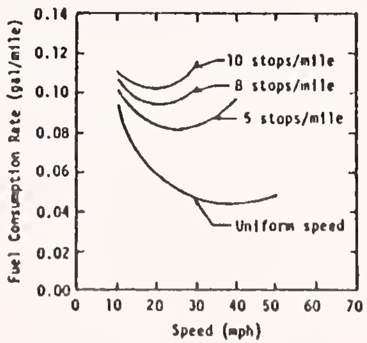
Excess gallons of gasoline consumed per slowdown cycle ("composite" vehicle):

Speed	Speed Reduction (mph) 10	20	30	40	50	60
20	0.0032	--	--	--	--	--
30	0.0035	0.0062	--	--	--	--
40	0.0038	0.0068	0.0093	--	--	--
50	0.0042	0.0074	0.0106	0.0140	--	--
60	0.0046	0.0082	0.0120	0.0155	0.0140	--
70	0.0051	0.0090	0.0130	0.0167	0.0203	0.0243

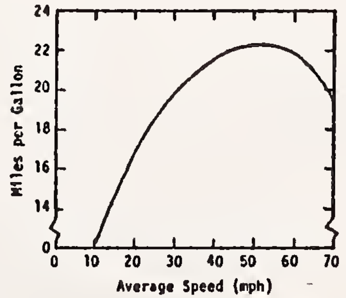
FACTOR #6 STOPS PER MILE

Source	Finding	Notes
Claffey, NCHRP Report 111, 1971 Claffey, FHWA, 1976 Winfrey, 1969 Claffey, HRB Bulletin 276, 1960 From Posey, K., Memorandum	• Excess fuel consumed for 1 stop at 50 mph is 0.017 gals. • Excess fuel consumption depends on vehicle weight, independent of acceleration/deceleration rates.	Uniform speed Composite vehicle 1 vs. 0 stops
EPA, 1976	• Stopping frequency vs. average speed (based on driving cycles)	
Johnson, et al., 1975 In Automotive Fuel Economy, 1975	• Stopping frequency vs. average speed--observed	

FACTOR #6 STOPS PER MILE (Continued)

May & Wagner, 1960 In Planning Environment International, 1977	• Urban Arterials	$T_m = \frac{T_t}{0.132T_t + 0.782}$ T_t = average total travel time, minutes/mile T_m = average time in motion, minutes/mile $T_m - T_t = T_s$ = average time stopped, minutes/mile T_s = 25 x stops/mile	Coefficient, T_s, depends on signal cycle time and varies between 21 and 29.
Winfrey, 1969 In Claffey, FHWA, 1976	• Excess gallons consumed per 1000 stop-cycles (4000-lb vehicle)	Running Speed (mph) — Excess Gallons 10 — 1.0 20 — 4.4 30 — 8.0 40 — 11.8 50 — 16.5 60 — 23.2	Claffey shows a considerable degree of variability exists between vehicles.
Claffey, FHWA, 1976	• Stops/mile		Typical curves shown in Claffey on an <u>individual</u> vehicle basis.

FACTOR #7 AVERAGE SPEED

Claffey, NCHRP Rpt. 111, 1971 Winfrey, 1969 Claffey, HRB Bulletin 276, 1960 From Posey, K., Memorandum	• Significant decreases in gpm from 10 to 30 mph then increases above 30 mph	Uniform speed Vehicle weight Level Straight Good surface
SAE Fuel Economy Task Force, 1975 In Automotive Fuel Economy, 1975	• Maximum fuel economy in mpg is generally between 40 and 55 mph	
Highway Capacity Manual, 1965	"It is not yet feasible to develop charts or curves presenting basic speed/volume relationships for extended sections of downtown streets....it is not possible to develop even typical speed-v/c relationships."	

FACTOR #7 AVERAGE SPEED (Continued)

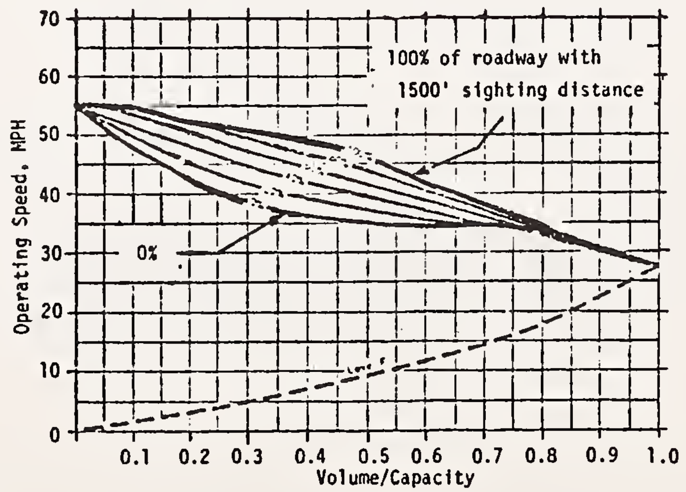
NCHRP 113 In Planning Environment International, 1977	• Mean velocity gradient is measure of the variability speed: $G = \frac{\delta}{\bar{v}}$ G = mean velocity gradient, sec^{-1} δ = acceleration noise, feet per sec^2 $\bar{v}$ = mean velocity, feet per sec $\delta^2 = \frac{1}{T}\int_0^T \left[\frac{dv}{dt} - \frac{d\bar{v}}{dt}\right]^2 dt \cong \frac{1}{T}\left(\frac{1}{\Delta T}\right) \Sigma\, \Delta v^2$ T = running time v = change in velocity in equal increments of Δv time ΔT	
Evans, et al. (GM) In Planning Environment International, 1977	• Three major determinants of fuel consumption per unit distance: - mean trip time (inverse of average speed) - work to accelerate vehicle - fraction of distance covered by severe deceleration, .15 m/sec^2	
Greenshields In Planning Environment International, 1977	$u = u_f(1 - k/k_j)$ u = average vehicle speed u_f = free flow speed k = vehicle density (vehicles/lane-mile) k_j = jam density $\cong$ 250 vehicles/lane-mile)	Postulated in 1930's and despite simplified form (e.g., $k = k_j$, $u = 0$), good predictor

FACTOR #8 TRAFFIC VOLUME

Source	Findings	Notes
Claffey, NCHRP Rpt. 111, 1971 From Posey, K., Memorandum	• 4% increase in gpm as VPH increased from 2800 to 5600 on 6-lane expressway (attempted speed 50 mph). • 6% increase in gpm as VPH increased from 1000 to 3000 on 6-lane arterial (attempted speed 40 mph). • 7% increase in gpm as VPH increased from 40 to 240 on 4-lane CBD street (attempted speed 25 mph).	4000-lb vehicle (VPH: Vehicles per hour)

Planning Environment International, 1977

- Relationships between volume/capacity ratio, operating speeds, average speeds and traffic flow conditions--from the Highway Capacity Manual, 1965.
- Level of service is related to available sighting distance.



- Average speed for two-lane rural road from Horn, 1961.
- Y (average vehicle speed) = 44.67 - 0.02X (roadway traffic volume for 15-minute increments) for developed areas.
- Y (average vehicle speed) = 47.67 - 0.02X (roadway traffic volume for 15-minute increments) for undeveloped areas.

FACTOR #8 TRAFFIC VOLUME (Continued)

Claffey, NCHRP 111, 1971

Correction factors to adjust average fuel consumption values for traffic volume on a six-lane expressway:

VPH	Attempted Speed (mph) 45			60
2400-2800	1.000	...	...	1.020
⋮	⋮			⋮
3600-4000	1.000	...	...	1.045
⋮	⋮			⋮
4800-5200	1.003	...	...	1.078
⋮	⋮			⋮
5000-6000	1.005	...	...	1.090

Correction factors to adjust average fuel consumption values for traffic volume for six-lane major street urban arterial with no parking:

VPH	Attempted Speed = 30 mph No Stops	....	2 Stops per Mile
1000-1200	1.000	....	1.460
⋮	⋮		⋮
1600-1800	1.010	....	1.460
⋮	⋮		⋮
2200-2400	1.010	....	1.460
⋮	⋮		⋮
2800-3000	1.050	....	1.460

Correction factors to adjust average fuel consumption values for traffic volume for six-lane CBD streets with parking on both sides:

VPH	Stops per Mile 0		3		6		9
0-40	1.0	...	1.55	...	2.12	...	2.65
⋮	⋮		⋮		⋮		⋮
120-160	1.0	...	1.60	...	2.20	...	2.75
⋮	⋮		⋮		⋮		⋮
240-280	-	...	1.74	...	2.39	...	2.91
⋮	⋮		⋮		⋮		⋮
360-400	-	...	-	...	2.68	...	3.18

- The higher the attempted speed the greater speed variability and fuel consumption.
- Stops have much greater effect than speed variation.
- Stops much more likely given traffic volume.
- Effect of stops is linear, effect of volume is nonlinear.

FACTOR #9 ATTEMPTED OR DESIGN SPEED

Chrysler, 1973 In MVMA, 1973	• "Jack rabbit starts" cause 18% increased fuel consumption. • Varying speed by 5 mph in 50-70 mph range reduces mpg 7-9%.
EPA, 1976	• Acceleration (2 mph/sec) requirements are 2-3 times steady speed cruising requirement. • At 50 mph about 20 hp is for rolling and aerodynamic losses and 55 hp for acceleration (at 2 mph/sec). • 22.5 mph cruising yields 20.0 mpg. Accelerating from 20 to 25 mph at 2 mph/sec yields 6.9 mpg (65% loss). Accelerating at 4 mph/sec yields 4.0 mpg (80% loss).
Scheffler & Niepoth, 1965 In Austin & Hellman, 1973	• 6ft/sec^2 acceleration vs. 12 ft/sec^2 causes 6% mpg loss. • Reducing acceleration to 3 ft/sec^2 causes 8% mpg gain.

FACTOR #9 ATTEMPTED OR DESIGN SPEED (Continued)

Forrester, et al., 1975

- Suburban driving style (2993 cc vehicle)

	mph	Journey Time Increase	mpg	mpg Improvement	Typical mpg
Severe	22	-	14.9	-	22
Mild	19	15.6%	17.1	14.8%	

- 1/2 mile intervals, acceleration to 40 mph followed by deceleration.
- 50% of total fuel used for acceleration, absolute quantity virtually independent of the acceleration rate.

Planning Environment International, 1977

- $S = 20.51 + 0.1147X_1 + 0.0005X_2 + 0.4333X_3 - 0.4072X_4$

  S = Mean spot speed

  X_1 = Percent of out-of-state cars

  X_2 = Minimum sighting distance (feet)

  X_3 = Posted speed limit

  X_4 = Roadside establishments (number per mile)

(For four-lane rural highways, Wortman, 1965)

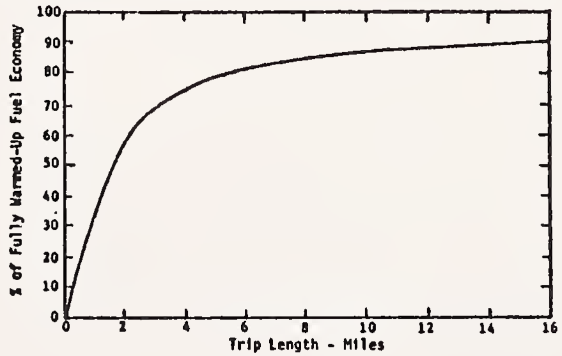
Elmberg & Michael, 1961 In Planning Environment International, 1977

- Average speed on suburban arterial streets was not significantly changed by changes in the posted speed limit (40, 35, 30 mph and none).

FACTOR #10 TRIP LENGTH

EPA, 1976

- Trip length and cold start fuel economy:



- Trips of 5 miles or less make up 15% of miles driven and 30% of gasoline consumed.

Eccleston, DOE, 1977

- Trip length and ambient temperature:

Trip Miles	Temperature °F 20	45	70	100
	Fuel consumed, gallons/100 miles			
0- 3.6	10.46	8.82	7.78	8.35
0- 7.5	9.01	8.05	7.39	8.20
0-11.1	8.38	7.69	7.15	8.00
0-21.3	6.85	6.46	6.15	6.90
0-31.6	6.25	5.99	5.75	6.47

- Seems like there is an optimum air temperature between 70°F and 100°F.

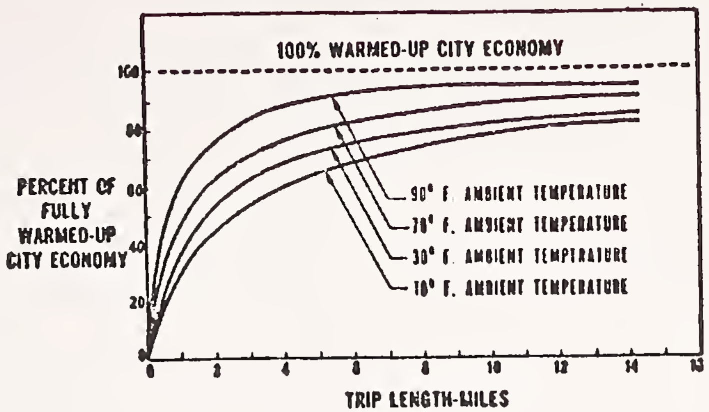
SAE Fuel Economy Task Force, 1975, in Automotive Fuel Economy, 1975

- Citing DOT/FHWA--90% of trips are less than 15 miles in length and represent 50% of all VMT.

FACTOR #10 TRIP LENGTH (Continued)

Scheffler & Niepoth, 1965, in Automotive Fuel Economy, 1975

- Trip length and ambient temperature:



- Fully warmed up city economy differs given ambient temperature--1 mpg higher at 70°F vs. 10°F.

Austin & Hellman, 1975 in Automotive Fuel Economy, 1975

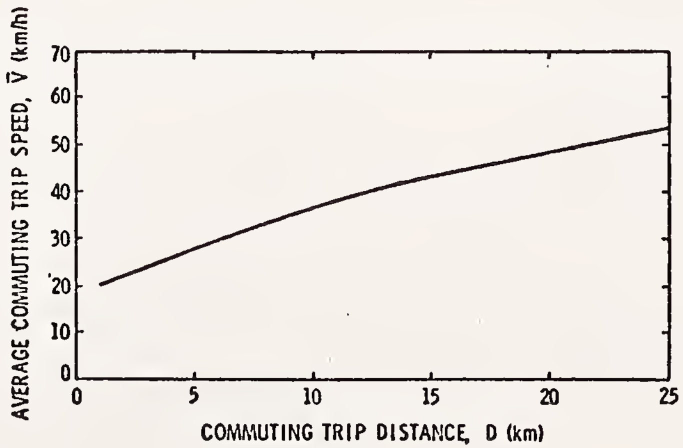
- Trip length:

Trip Length Category Miles	Normalized % of Trips (per mile)	% VMT in Category	Average MPH
1/2	17.0	0.24	2.5
1	15.9	1.82	7.5
2	13.5	3.10	10.9
3	10.0	3.44	15.0
4	6.4	2.94	16.0
5	8.2	4.70	18.8
6	3.9	2.68	20.0
7	3.0	2.41	21.0
8	3.4	3.12	21.8
9	1.2	1.24	23.5
10	5.5	6.31	25.0
11-15	1.62	12.08	24.4
16-20	0.86	8.88	25.7
21-30	0.40	11.70	31.2
31-40	0.16	6.51	28.0
41-50	0.09	4.70	31.9
51-99	0.02	9.46	36.7
100+	0.01	14.68	?

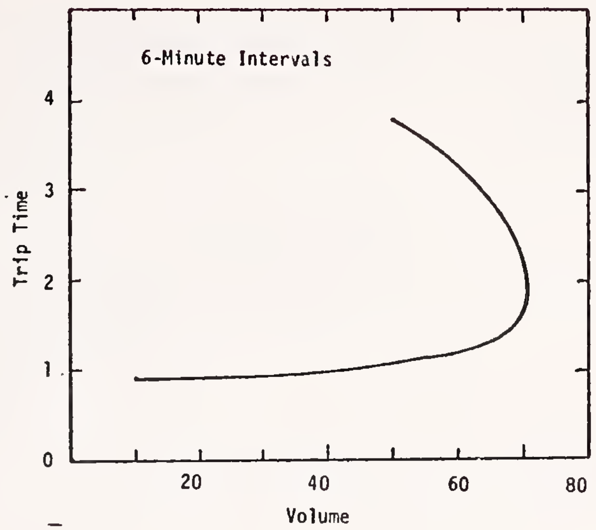
- FHWA reported data from NPTS.
- Bias towards numbers "5" and "10."
- % VMT in 100^{+} category 15%.
- Average MPH are estimated by a simplistic procedure (dividing reported travel distance by travel time) and do not reflect true average speed because portal to portal time is included. A closer look at the data suggests travel speeds of 21 mph for short trips and more than 60 mph for longer ones.

FACTOR #10 TRIP LENGTH (Continued)

Chang, Evans, Herman, etc., 1976	• Empirically observed relationship between commuting distance and trip speed:



FACTOR #10 TRIP LENGTH (Continued)

Rothrock & Keefer, 1956, in Planning Environment International, 1977	• Characteristics of trip time vs. traffic volume: 	• Backward bending curve indicating congestion and delay above critical volume.
Torres, in Planning Environment International, 1977	• Traffic signal density followed by % green time are the most important variables affecting travel time.	

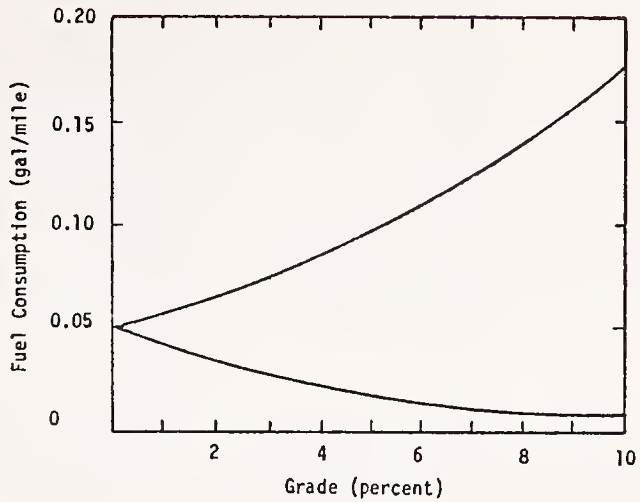
FACTOR #11 GRADES

Claffey, NCHRP Report 111, 1971	• 70% decrease in gpm for 10% grade at 30 mph for 4000-lb vehicle.	Uniform speed Straight roadway Good pavement Calm wind 80°-90°F	From Posey, K., Memorandum
Claffey, FHWA, 1976	• 40% decrease in gpm	(Same as above) 1972 Chevrolet	
Winfrey, 1969	• 70% decrease in gpm	Straight Good pavement	
MVMA, 1973	• Grade load horsepower = K_4WVG where K_4 is a constant W is car weight V is car speed G is grade		
EPA, 1976	• 3% grade--32% loss mpg • 7% grade--55% loss mpg	50 mph cruising	
Planning Environment International, 1977	• Car speeds seem independent of grade up to 4%. • Passenger car drivers seem to limit continuous demand on vehicle to 0.65 to 0.70 of maximum available power. • Lower powered cars have greater speed reduction on grades.		

FACTOR #11 GRADES (Continued)

Claffey, FHWA, 1976

- Grade vs. cruising speed:



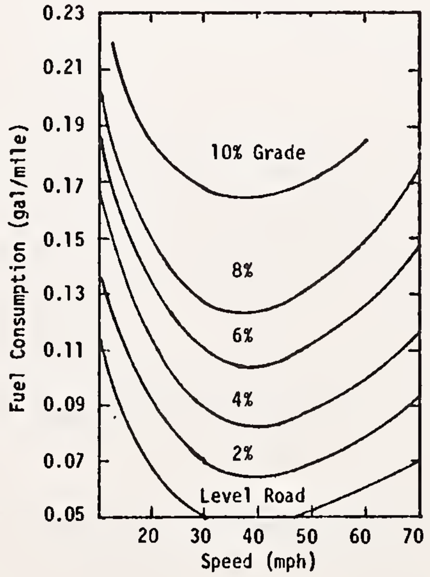
- These graphs are generated from from data collected on 1972 Chevrolet sedan.
- Fuel consumption on downhill grades is <u>not</u> a similar constant difference but one which increases with speed.

FACTOR #11 GRADES (Continued)

Claffey, NCHRP 111, 1971

- Table 6 shows automobile fuel consumption as affected by speed and gradient (up to 10% plus and minus)--straight high-type pavement and free flowing traffic--for composite passenger cars--large cars, 20%; standard cars, 65%; compact cars, 10%; small cars, 5%.

- Grade vs. speed graphs:



- Graphs show that benefit of going downhill does not increase indefinitely.
- At greater than certain grades, the benefit of going downhill doesn't compensate for the penalty of going uphill.

FACTOR #12 GEOGRAPHICAL AREA

SAE Fuel Economy Task Force, 1975, in Automotive Fuel Economy, 1975	• Acceleration profile: SAE standard (0-30 mph) is faster than observed acceleration in five cities--N.Y.C., Chicago, Cincinnati, Houston, Los Angeles (N.Y.C. the fastest, and L.A. the slowest observed).
Claffey, FHWA, 1972	• Average statewide fuel consumption rates by type of vehicle (small passenger car, compact and standard cars, single unit truck, and truck combinations) for roads typical of the Principal Federal Aid Systems (rural and urban, interstate, primary and secondary). • Average fuel consumption by type and vehicle by terrain type (mountainous, rolling, flat), range of gradient (0-2%, 2-4%, 4-6%, 6-8%), vehicle stops per mile, and travel conditions (rural and urban, free-flowing and congested).
Chang, Evans, Herman, etc., 1976	• In studying fuel consumption under urban traffic conditions many results and conclusions were reached: 1. Fuel consumption per unit distance could be sufficiently described as the function: $\phi = k_1 + k_2\bar{t}$ where ϕ is the fuel consumption per unit distance. k_1 is a constant proportional to vehicle mass and relates to overcoming inertia. k_2 is a constant related to overcoming mechanical losses. $\bar{t}$ is the average time per unit distance. Generally, they found $\phi = 112 + 1.05\bar{t}$ for a typical GM car.

FACTOR # 12 GEOGRAPHICAL AREA (Continued)

Chang, Evans, Herman, etc., 1976 (Continued)

2. In a multivariate analysis of fuel consumption the three most signifcant factors were:

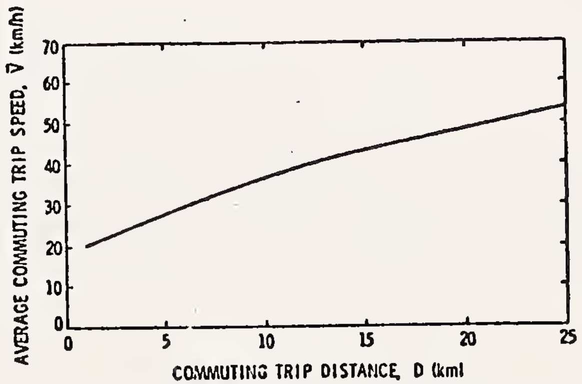
   a) Trip time per unit distance (inverse of average speed).

   b) Acceleration per unit distance (work).

   c) Percentage of high decelerations.

   With regard to the trip map, high decelerations have to have corresponding high accelerations in order to maintain average travel speed which is influenced by traffic volume, etc. (Author's note)

3. An empirically observed relationship exists between commuting distance and trip speed:



This relationship is important for cold start trips (see ambient temperature factor).

FACTOR #13 HIGHWAY SYSTEM

Johnson, et al., 1975, in Automotive Fuel Economy, 1975

- Observed Stopping Frequency and Speed:

Road Type	Average Speed	Stops per Mile	Percent Usage
Expressway	53.1	0.03	19
Expressway-Business Route	46.7	0.07	14
Rural Highway	44.7	0.10	8
Suburban Artery	28.6	0.77	16
Unpaved Rural	24.5	0.55	--
Urban Artery	23.0	1.29	25
Strip Commercial	22.2	1.41	7
Suburban-No Curb	21.5	0.80	--
Suburban-Curb	19.6	1.16	±
Unpaved-Suburban	17.7	0.37	--
CBD-No Parking	17.2	2.55	1
Urban	17.2	1.77	4
CBD-Parking	12.4	3.80	3
Shopping Center	11.5	4.35	--

Austin, et al., 1974, in Automotive Fuel Economy, 1975

- Stopping Frequency and Average Speed:

Road Type	Average Speed	Stops per Mile	Speed Deviation per Mile
Principal Arterial	57.16	0.010	0.07
Minor Arterial	49.42	0.057	0.44
Collector	45.80	0.126	0.48
Local	39.78	0.236	0.59

- Average speeds seem higher than above.
- Deviations are ± 5 mph.

FACTOR #13 HIGHWAY SYSTEM (Continued)

Sturm, DOT/TSC, 1975

- Functional Classification

  Urban
  - Principal Arterial System
    - Urban Extension of Rural Principal Arterial
    - Urban Extension of Rural Minor Arterial
    - Other Urban Principal Arterials
  - Minor Arterial System
  - Collector Street System
  - Local Street System

  Rural
  - Principal Arterial System
    - Interstate
    - Other Principal Arterials
  - Minor Arterial System
  - Collector Road System
    - Major Collector Roads
    - Minor Collector Roads
  - Local Road System

Wu & Crout, DOT/TSC, 1975

- VMT Distribution

Classification	VMT (Billions)	% VMT	Median Speed
Urban			
Interstate	122	9.6	57
Urban Extensions of Rural Principal and Minor Arterials	159	12.5	42
Other Urban Principal and Minor Arterial Systems; Collector Streets	125	9.8	40
Other	272	21.5	--
Rural			
Interstate	118	9.2	67
Principal and Minor Arterials	210	16.7	58
Major Collectors	153	12.1	53
Other	109	8.6	--
	1,268		

- Speed distribution for urban extensions and minor arterials is bimodal.

FACTOR #13 HIGHWAY SYSTEM (Continued)

Planning Environment International, 1977	• One-way streets had substantially lower travel times (25% greater) than two-way streets.	
Webster, in Planning Environment International, 1977	• Saturation: S = 160w S = saturation flow in passenger cars per hour w = street width in feet Also S decreased 3% for each 1° of grade and medium or heavy truck = 1-3/2 passenger car bus = 2-1/4 passenger car light truck or van = 1 passenger car motorcycle or scooter = 1/3 passenger car	
Claffey, FHWA, 1972	• Tables in Report - Distribution of Speeds by Vehicle Category (passenger cars including pickup and panel trucks vs. single-unit trucks and truck combinations), Highway System (interstate, F-A primary, F-A secondary and Non F-A), and Travel Conditions (free-flowing and congested, rural and urban). - Distribution of Terrain Types (mountainous, rolling and flat) by Highway System (by State). - Distribution of Road Gradient by Terrain Type and Highway System (by geographical area). - Distribution of Travel by Single-Unit Trucks and Truck Combinations Among Federal Aid Highway Systems (by State).	Based on Highway Capacity Manual, 1965.

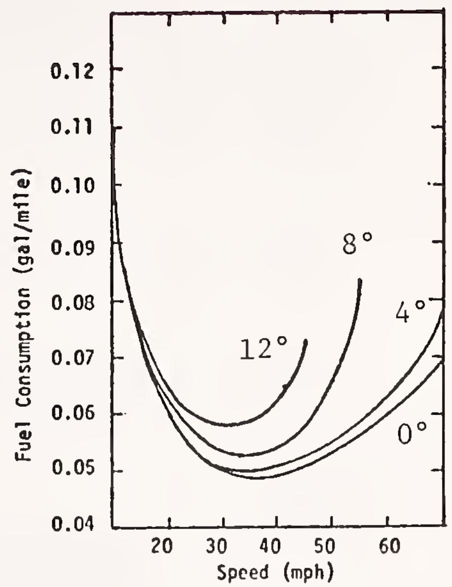
FACTOR #14 CURVATURE

Source	Findings	Conditions	Reference
Claffey, NCHRP Report 111, 1971	• For 4000-lb car and a 12° curve, the increases in gpm were: $\frac{20\text{ mph}}{11\%}$ and $\frac{50\text{ mph}}{115\%}$	Uniform speed Level road Good pavement Calm wind 80°-90°F	In Posey, K., Memorandum
Claffey, FHWA, 1976	• 18% and 40%	(Same as above) 1972 Chevrolet	
Winfrey, 1969	• 15% and 27%	Good pavement	
Planning Environment International, 1977	• For rural roads $V_m = 46.26 - 0.746D$ V_m = mean observed velocity D = curvature • $S = 56.8 - \frac{75.4}{M+1}$ (for inside lanes) $S = 55.6 - \frac{80.2}{M+1}$ S = average spot speed M = minimum sight distance (in hundreds of feet) on curves		

FACTOR #14 CURVATURE (Continued)

Claffey, FHWA, 1976

- The curves are:



FACTOR #15 HIGHWAY SURFACE INCLUDING ICE AND SNOW

Claffey, NCHRP Report 111, 1971	• For 4000-lb car gravel increases gpm 20-30% at 30 mph, 70% at 50 mph.	Straight Level Calm wind 80°-90°F	From Posey K., Memorandum
Winfrey, 1969	• According to Winfrey the increase is 20% at 50 mph.	Straight Level	
Claffey, HRB Bullètin 276, 1960	• Early Claffey work indicates only a 20% increase at 50 mph.	Straight Level	
Claffey, FHWA, 1972	• Hard packed snow causes 20% increase in gpm at 30 mph on hard packed snow, and 54% increase in gpm at 30 mph on 2" of new snow on hard packed snow.	Straight Level Good surface 4000-lb Chevrolet 283 cu.in., V-8 Automatic Calm wind 25°-30°F	

FACTOR #15 HIGHWAY SURFACE INCLUDING ICE AND SNOW (Continued)

American Motors, 1973, in MVMA, 1973	• Wet or snow covered pavement can cause up to 1 mpg loss-- 7% for 15 mpg vehicle.
EPA, 1976	• For various road conditions, at 50 mph: (Vehicle was not specified) Broken and patched asphalt —— 15% mpg loss Gravel —— 35% mpg loss Dry sand —— 45% mpg loss
Claffey, NCHRP 111, 1971	• For a 4400-lb sedan, increase in fuel consumption (gpm) was:

	20 mph	30 mph	50 mph
Broken and patched asphalt	5%	20%	50%
Well packed gravel	13%	26%	70%
Loose sand	28%	40%	100%

FACTOR #16 VEHICLE CHARACTERISTICS

WEIGHT

Source	Findings	Comments
Marks & Niepoth, 1975	• Sensitivity of fuel consumed to weight increases: Additional Fuel Consumed in 10,000 Miles for 100-lb Increase / Test Cycle: 16.8 — SAE-URB 12.8 — EPA-URB 12.8 — GM CITY-SUB 11.0 — EPA-55/45 8.7 — EPA-HWY	• Results are based on GM General Purpose Performance and Economy Simulation Model (GPSIM). • 100-lb weight reduction with a fixed axle ratio results in a decrease of 7 gallons/10,000 miles, and a decrease in 0-60 mph acceleration time by 0.4 seconds. If acceleration performance is kept constant by lowering the axle ratio, the fuel consumption reduction increases to 16 gallons/10,000 miles.
Huebner & Gasser, Chrysler, 1973	• 10% decrease in weight (~ 400 lbs.): - 0.4 mpg increase in 70 mpg road load economy (4%) - 0.5 mpg increase in urban cycle economy (2%)	
Starkman & Marks, 1973	• Increase of 1.5 to 2.5 mpg for 1000-lb reduction weight in city driving, 1.0 mpg in highway economy.	
Chrysler, 1973, in MVMA, 1973	• Increase of 0.2 mpg for 100-lb decrease (~ 1%)	
Stempel & Martens, 1974, in Automotive Fuel Economy, 1975	• Additional consumption due to weight increase: - Subcompact: 8 gals/100 lb per 10,000 miles (2%) - Full size: 7 gals/100 lb per 10,000 miles (1%)	

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

Source	Findings
MacDonald, 1973 in MVMA, 1973	• Weight penalty greater for small cars: - 0.4 mpg decrease for 100 lb for subcompact - 0.1 mpg decrease for 100 lb for standard size car
Claffey, NCHRP 111, 1971, from Posey, K., Memorandum	• On level roads, greatest effect is at lower speeds. • 20% increase in gpm for 4500 vs. 4000-lb car at 80 mph. • On grades, weight affects all speeds--10% grade, 60 mph, 10% increase in gpm (4500 vs. 4000-lb vehicle).
MVMA, 1973	• Acceleration horsepower load = kVWC where k is a constant V is car speed W is car weight C is acceleration rate
ENGINE CHARACTERISTICS	
EPA, 1976	• Engine efficiency is a function of: 1. Air-fuel ratio (carburetion) 2. Compression ratio 3. Engine load factor 4. Engine speed 5. Spark timing 6. Others = number of cylinders, bore stroke and dimensions, number of rings, valve size, etc.
Murrell, 1975	• Based on regression, the most significant determinant of fuel economy is CID x N/V--cubic inch displacement and the RPM/MPH ratio.

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

LaPointe, 1973	• Regression equation for fuel consumption = $k(\text{weight})^a\ (\text{displacement})^b\ (\text{axle ratio})^c$ where $k = 5.248 \times 10^{-4}$ $a = 0.3067$ $b = 0.3469$ $R^2 = 0.932$ $c = 0.3395$	
Huebner & Gasser, 1973 in MVMA, 1973	• 10% increase in displacement - Decrease of 0.1 mpg at 70 mph road load. - Decrease of 0.2 mpg on urban drive cycle. - 12% decrease in acceleration time through gears. - 19% decrease in acceleration from 50 to 70 mph.	V8 engine Automatic transmission Intermediate size car
Claffey, NCHRP 111, 1971 from Posey, K., Memorandum	• 440 cu.in. vs. 300 cu.in. yields 17% increase in gpm at 60 mph and 6% grade.	V8 engine Automatic transmission 4400-lb vehicle
Huebner & Gasser, 1973 in MVMA, 1973	• 10% increase in compression ratio from 8.6:1 to 9.5:1 - Increase of 0.5 mpg at 70 mph road load. - Increase of 0.3 mpg on urban crive cycle. - 4% decrease in acceleration time through gears. - 6% decrease in acceleration time from 50 to 70 mph.	

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

EPA, 1976

- Compression ratio ranges between 8:1 to 12:1.
- Relative efficiency of higher compression engines is greater at lower speeds.
- "For a given speed and load, a small engine operating at a high load factor will have higher efficiency and better fuel economy than a larger engine running at a low load factor."
- "A decrease in engine speed usually increases efficiency. This occurs because lower speeds give lower internal friction and throttling losses."
- "The proper ignition time is a function of the flame speed in the combustible gas, and must be varied with engine RPM and engine load."
- "High energy ignition has no direct economy effect, but can promote leaner A/F ratios and improve engine durability.

Cantwell, et al., 1976

- Advancing spark timing by 5°:

Model Year	Composite Fuel Economy Improvement (%)
1970	2
1971-74	3
1975 (non-catalyst)	3
1975 (catalyst)	2
1976 (catalyst)	3

- Spark advance to improve fuel economy increases octane requirements above 91 RON--to 93 to 99 RON.

Chrysler, 1973 in MVMA, 1973 (Also in EPA, 1976)

- Given spark plug misfiring 50% of time at 60 mph yields 7.3% decrease in mpg.

EPA, 1976

- Maximum fuel efficiency is at an air-fuel ratio of 17:1.
- NO_x emissions are greatest at this point.

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

Percival & Ahrens, 1967 in Austin & Hellman, 1973	• Turbochargers can yield: - 12.7% improvement in mpg in city driving cycle. - 11.5% improvement in highway mpg.	
Honda, 1973 in Austin & Hellman, 1973	• Stratified charge engines experience 10% improvement in fuel economy as well as increases in power.	
TIRES AND ROLLING RESISTANCE		
Cornell, 1965 in MVMA, 1973	• Rolling resistance amounts to approximately 10 horsepower at 50 mph and 15 horsepower at 70 mph.	• Friction losses in the drive line system make up the bulk of the vehicle's total rolling resistance; front wheel rolling resistance accounts for the remainder. Rolling resistance losses are caused by wheel bearing friction, tire rolling friction, universal joint friction, friction in the differential gears, and transmission losses--primarily torque converter slippage within an automatic transmission--and any brake drag which may occur.
EPA, 1976	• 20% less rolling friction, radial vs. bias ply tires. • 7% loss in mpg at 50 mph cruising speed and 35% tire under inflation.	

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

Source	Findings
Stempel & Martens, 1974 in Automotive Fuel Economy, 1975	• Differences in mpg given different tires and tests:
Starkman & Marks, 1973 in MVMA, 1973	• Tire rolling resistance is the major contribution to the total force required to propel the car at low speeds.
Chrysler, 1973 in MVMA, 1973	• Under-inflation of tires can reduce fuel economy by 1.0 mpg.
Claffey, FHWA, 1976	• Radials decrease gpm 6% at 24 psi and speeds of 30-55 mph. • A decrease of tire pressure by 20% increases gpm by 1 to 10%.
Chrysler, 1973 in MVMA, 1973 (Also in EPA, 1976)	• 0.25 inches of improper front wheel alignment can result in a 0.3 mpg (2%) loss.

Table for Stempel & Martens, 1974:

Car	Tire	MPG: Road Test	MPG: Dynamometer
Subcompact	Belted	22.4	22.3
	Radial	23.1	22.5
	Difference	+3.1%	+0.9%
Sports	Belted	17.4	16.3
	Radial	17.6	16.0
	Difference	+1.2%	-1.8%
Full Size	Belted	14.8	14.5
	Radial	15.3	14.1
	Difference	+3.4%	-2.8%

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

<u>TRANSMISSION</u>		
Cornell, 1965, in Automotive Fuel Economy, 1975	• At speeds below ~35 mph the manual transmission is more fuel efficient. Above 35 mph the automatic transmission is more efficient.	• Torque converter slip is a greater percent of frictional losses at low speeds.
Austin & Hellman, 1973	• Above 3000-lb inertial weight there is no penalty of automatic transmission. • For lighter vehicles there is a 6% reduction in mpg.	
Heubner & Gasser, 1973, in MVMA, 1973	• Switching from manual to automatic transmission causes a 1.2 mpg loss at 70 mph and a 1.8 mpg loss in urban driving. However, there is a 6-16% gain in acceleration (given a constant rear axle ratio). • A 10% decrease in the rear axle ratio yields a 0.6 mpg gain at 70 mph and a 0.2 mpg gain in urban driving. There is also a 3-5% loss in acceleration. • Given a "tight" vs. "loose" torque converter, there was a 0.2 mpg gain at 70 mph and a 0.7 mpg gain in urban driving (1-6% acceleration loss).	

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

Hurter & Lee, 1975, in Automotive Fuel Economy, 1975

- Breakdown of fuel consumption in propelling vehicle (in %):

Vehicle	Accessories	Transmission	Rolling	Drag	MPG
20 mph					
350 CID	19%	12	59	10	15.7
400	22	16	52	10	16.1
250	22	14	53	11	20.0
250	21	13	55	11	24.9
40 mph					
350	10	14	46	30	18.5
400	14	12	44	30	19.8
250	14	12	40	35	20.4
250	16	12	40	32	27.1
60 mph					
350	7	12	33	48	15.4
400	11	11	38	40	16.5
250	9	10	27	54	16.9
250	10	11	28	51	20.7

- 4-speed automatic with torque converter lock-up 12% gain.
- Continuously variable transmission has a projected ~ 22% improvement.

POWER ACCESSORIES

EPA, 1976

- Effect of power devices on mpg at 30 mph:

Accessory	Weight Effect	Power Drain
Fan	0.1%	2-3%
Alternator	0.2%	5-20%
Power Steering	0.3%	5-9%
Air Conditioning	1.2%	30-50%

Cornell, 1965, in Automotive Fuel Economy

- Fuel economy loss due to power steering decreases with vehicle speed from ~ 0.7 mpg at 25 mph to ~ 0.25 mpg at 90 mph.
- "Power steering has essentially constant torque requirement over speed ranges. At higher speeds,....the torque required to drive the power steering pump is obtained at a more economic level of engine output."

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

Claffey, FHWA, 1972	• The presence of power steering, power brakes, and emission control devices cause an increase of gpm by 10%.
Heubner & Gasser, 1973, in MVMA, 1973	• Alternator output of 40-50 amperes decreases urban and highway test cycle mpg by 0.9 and 0.5 mpg.
Claffey, FHWA, 1976	• Headlights on (at night) have no significant effect (0.0002 gpm).
<u>EFFECT OF TUNE-UP</u>	
Claffey, FHWA, 1976	• Effect of tune-up is independent of vehicle age or mileage since last tune-up. • Effect is significant only if it cures a mechanical defect. • Benefited primarily vehicles operated in urban areas.
Panzer, 1976	• Amount of mpg increase varies from ~12.5 to ~14.5% as urban mileage increases from 20% to 80%. • Fuel economy improvements are greatest for repairs of misfiring, air/fuel mix too rich, and timing.
Chrysler, 1973, in MVMA, 1973	• 5° spark retard from manufacturer's specifications causes 1 mpg loss.
EPA, 1972, in Austin & Hellman, 1973	• Benefit of tune-up ranges from 0 to 6%.

FACTOR #16 VEHICLE CHARACTERISTICS (Continued)

FUEL	
Schultz, et al., 1976	• Diesels have a 50% better mpg performance in the steady state over gasoline engines. • For cold start/cold run conditions the diesel performance is more than 100% better. • Diesel fuel consumption during idling is one-quarter that of gasoline engines. • Throttling losses are minimal because the diesel doesn't have a throttle. • Greatest benefits are at speeds under 30 mph (100%+).
Claffey, NCHRP 111, 1971	• Significant differences between gasoline engine and diesel engine trucks, ~ 30% at 50 mph.
Austin & Hellman, 1973	• Highly boosted diesels do not suffer loss of fuel economy like gasoline engines.
Ingamells, 1974, in Automotive Fuel Economy, 1975	• Heat content (in Btu/gallon) varies between 110,000 and 115,000 Btu gallon of gasoline. • Fuel economy increases by 0.5% for every 1% increase in Btu content.
OTHER VEHICLE FACTORS	
Cornell, 1965, in Automotive Fuel Economy, 1975	• Aerodynamic drag which is based on vehicle size accounts for 20% of fuel economy difference between full size and compact car at 70 mph.

FACTOR #16 VEHICLE CHARACTERISTICS (Concluded)

Claffey, NCHRP 111, 1971	• Fuel consumption increases 5% after 60,000 miles.
Chrysler, 1973, in MVMA, 1973	• Exhaust gas recirculation emission control devices account for 0.5 mpg loss in average fuel economy between 1972 and 1973.
EPA, 1976	• Added emission control devices required by California increased fuel economy for three manufacturers and decreased it for six.

APPENDIX C: GENERATION OF THE VMT MATRIX FROM INCOMPLETE INFORMATION

There are two purposes to this appendix. The first is to develop a VMT matrix so that it can be used in the illustrative examples worked out in Appendix D. The second purpose is to illustrate some of the methods for developing the maxtrix which is described in Section 4.0. Because of its illustrative nature, the VMT matrix which is developed is much smaller than the matrix proposed for Phase II.

The variables used are:

1. Trip length (5 categories)
2. Trip purpose (5 categories)
3. Season (4 categories)
4. Time of day the trip was started (3 categories defined as "day", "night", and "commuting hours").

It is possible to generate the complete matrix from the original NPTS data, but only partial information is readily available in published form. Using only this limited information put us into nearly the same position as having to combine data from several sources with only partially overlapping information.

Tabulations published in NPTS reports are:

- Trip Length by Purpose. Estimates for the year, from the unpublished table NPT:T-5. A slightly different and less detailed breakdown is given in Table A-19, P. 81 of NPTS Report No. 10 (May, 1974).
- Trip Purpose by Season. From Table 2, P. 11 of NPTS Report No. 3 (April, 1972).
- Trip Season by Length. From Table 5, P. 15 of NPTS Report No. 3 (April, 1972).
- Trip Purpose by Time of Day. From NPTS Report No. 10, Table A-13, P. 75.

These tables refer to trip counts; similar tables referring to vehicle miles of travel are available. Time of day occurs only in one table, so that more detailed information on trip length and season can only affect time of day through trip purpose: i.e., for a fixed trip purpose with tables, there can be no rationale for interactions between time of day and trip length by season. The main complication is then using the first three 2 dimensional tables to generate a 3 dimensional matrix: trip length by purpose by season.

The Deming-Stephan (1940) algorithm [1] -- now called iterative proportional fitting [2] -- is used to generate the 3 dimensional matrix: the maxtrix is initially

filled with 1's, and the dimensions are taken in order, the entries in the table being adjusted proportionately to give the correct marginal table. The algorithm converges in this case so long as the marginals are consistent with one another.

Next, each slice of the matrix corresponding to a trip purpose is split appropriately over time of day, and thus is produced the 4 dimensional matrix.

The technique is illustrated here for counts. It could also be used for the VMT in each cell, but then the following point becomes much more important. As originally derived, the Deming-Stephan algorithm was a least squares adjustment of values in a table to fit given marginals. A weighted least squares procedure was used, which essentially assumed Poisson distributions in the cells prior to conditioning. In fact, for the trip counts, such an assumption is not very realistic. For VMT, the assumption is worse. Thus the iterative proportional fitting can be used as a "Standard Technique" but different and perhaps better methods of filling in the matrix from the marginals could be derived.

For VMT estimates when trip length is one dimension of the matrix, it is not immediately obvious that iterative proportional fitting of VMT and, separately, counts, leads to average trip lengths in cells in the body of the matrix that lie within the appropriate trip length categories. For these reasons, only the counts, which are not constrained in this way, were used.

Table C-1, therefore presents the VMT matrix of trip counts. In order to estimate VMT, average trip length per trip category was computed from information on NPTS in Appendix D of [3]. The average trip lengths were not adjusted for seasonal differences which one could expect, due to longer summer vacation trips. However, the simpler assumption results in a 3 percent error between VMT estimate, based on the model developed here and the VMT estimate reported by FHWA based on NPTS data.

TABLE C-1

FOUR-DIMENSIONAL TRIP COUNT MATRIX DERIVED FROM FOUR MARGINAL MATRICES

Trip Length	Spring			Summer			Fall			Winter			
	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night	
≤ 1 mile	282	734	163	258	672	150	277	721	160	315	820	183	Between Home & Work
2-3 miles	317	825	184	318	828	184	352	917	204	343	892	198	
4-10 miles	593	1544	343	590	1537	341	608	1583	351	578	1505	334	
10-15 miles	205	534	119	184	479	107	170	442	99	179	465	104	
16+ miles	290	755	168	283	736	164	253	659	147	271	705	157	
	76	44	23	102	59	31	95	55	29	100	58	30	Other Business
	81	47	25	119	69	36	114	66	34	104	60	31	
	126	73	38	183	106	55	164	94	49	145	84	44	
	42	24	13	55	32	17	44	26	14	43	25	13	
	102	59	31	146	84	44	114	66	34	113	65	34	
	1234	722	441	1110	649	397	1044	611	374	1081	632	387	Family
	1010	591	361	995	582	356	966	565	346	854	500	306	
	1116	653	399	1091	638	390	985	576	353	852	498	305	
	242	142	87	214	125	77	173	102	62	165	97	60	
	238	139	86	228	134	82	179	105	65	174	102	63	
	327	290	482	323	287	476	289	257	427	270	240	399	Social & Recreational
	316	281	467	342	304	505	317	282	468	253	225	373	
	497	442	735	534	474	788	460	409	679	358	319	529	
	154	137	227	149	132	220	115	102	170	99	88	146	
	287	255	423	302	268	446	226	201	334	198	176	292	
	409	343	147	171	143	62	388	326	140	388	325	139	Other
	358	300	129	164	137	59	384	322	138	328	275	118	
	341	286	123	154	130	56	337	283	121	281	236	101	
	72	60	26	30	25	11	58	48	21	53	45	20	
	78	65	29	35	30	13	66	55	24	62	52	23	

The average trip length per category estimate was:

- ≤ 1 mile 0.75 miles
- 2-3 miles 2.50 miles
- 4-10 miles 6.50 miles
- 11-15 miles 12.50 miles
- 16+ miles 37.50 miles.

References:

[1] Deming, W. E. and F. F. Stephan, "On a Least Squares Adjustment of a Sampled Frequency Table when the Expected Marginal Totals are known" *Amer. Math Statistics* 11, 1940, 427-444.

[2] Bishop, Y.M.M., S. Fienberg, and P. W. Holland. *Discrete Multivariate Analysis* Theory and Practice, MIT Press, 1975.

[3] Austin, T. C. and K. H. Hellman. *Passenger Car Fuel Economy or Influence by Trip Length,* Society of Automative Engineer, Warrendale, Pa., 1975. (SAE Paper No. 75004)

APPENDIX D: ILLUSTRATIVE EXAMPLES OF THE USES OF A DRIVING CONDITION MODEL

In this report, a model has been outlined which is designed to help decision makers and analysts answer certain types of questions about personal travel (the amount under certain conditions and the corrolary fuel consumption). The size of the proposed model is too large to be used in an illustrative example. (Further, the exact structure and content of the model are not known since the model has not been developed.) However, it is important to see what such a model might be used for, if only on a rudimentary level. Therefore, two examples have been formulated which rely on the 1969 Nationwide Personal Transportation Study and other sources. The first example deals with the effect of the fuel economy penalty associated with temperatures and trip length. (At low temperatures and on short trips, vehicles fall considerably short of their fully warmed up fuel economy.) The second example deals with what the effect would be of eliminating some short personal vehicle trips, e.g. 50 percent of the commuter trips of one mile or less in length.

Ideally, in order to look at the effect of temperature and trip length using the driving condition matrix, one would focus on a few specific questions. For instance,

- What is the fuel consumption rate for winter trips versus summer trips?
- What is the fuel consumption rate for short (3 miles or less) winter or summer trips versus the fuel consumption rate for longer trips (over 15 miles)?
- What is the excess fuel consumption due to lower winter temperatures?

Basically, the manipulations of the model would be very simple. In the first case, one would compute the average fuel consumption rate weighted by VMT in each trip length category for the summer and winter months. In the second case, there would be additional computations segmented; the weighted average fuel consumption rate for short trips and longer trips both in winter and summer months would be computed. The third question would require several manipulations, one to compute what the total winter fuel consumption (simply summing across the winter month cells) would be, the next would be to compute what fuel consumption would have been (multiply summer fuel consumption rates by winter VMT per trip length and then sum).

However, we cannot illustrate the use of the proposed model so simply. Even a relatively simple but still realistic model would have several thousand cells. Using available data and following as well as possible the plans we have laid out in the study, we have constructed very reduced driving condition matrices of VMT and fuel consumption. The dimensions of these matrices are trip purpose, trip length, and time, with a total of 300 cells each. Trip purpose has five dimensions; trip length, five; and time, twelve (three per day for four seasons). The derivation of the VMT estimates were based on the 1969-1970 NPTS (See Appendix C.)

The derivation of the fuel consumption rates is given at the end of this appendix. Both of the matrices are limited by the amount of time and data available to construct them. However, we believe that they reflect many of the significant characteristics of the proposed model and do practically illustrate the examples selected.

Shown below is a reduced VMT matrix (all trip purposes are combined):

Table D-1

Vehicle-Miles of Travel and Number of Trips by Trip Length and Time

Trip Length	Spring			Summer			Fall			Winter		
	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night	Oay	Commute	Night
≤ 1	2,328	2,133	1,256	1,964	1,810	1,116	2,093	1,970	1,130	2,154	2,075	1,138
	1,746	1,600	942	1,473	1,357	837	1,569	1,477	847	1,615	1,556	853
2-3	2,082	2,044	1,166	1,938	1,920	1,140	2,133	2,152	1,190	1,882	1,952	1,026
	5,205	5,110	2,915	4,845	4,800	2,850	5,332	5,380	2,975	4,705	4,880	2,565
4-10	2,673	2,998	1,638	2,552	2,885	1,630	2,554	2,945	1,553	2,214	2,642	1,313
	17,374	19,487	10,647	16,588	18,752	10,595	16,601	19,142	10,094	14,391	17,173	8,534
11-15	715	897	472	632	793	432	560	720	366	539	720	343
	8,937	11,212	5,900	7,900	9,912	5,400	7,000	9,000	4,575	6,737	9,000	4,287
16+	995	1,273	737	994	1,252	749	838	1,086	604	818	1,100	569
	37,312	47,737	27,637	37,275	46,950	28,087	31,425	40,725	22,650	30,675	41,250	21,337
Total	9,810	9,435	5,269	8,080	8,660	5,067	8,178	8,873	4,843	7,607	8,489	4,389
	70,574	85,146	48,041	68,081	81,771	47,769	61,927	75,724	41,141	58,123	73,859	37,576

Note: The upper entry is number of trips (in thousands) and the lower entry, number of vehicle miles (in thousands).

The fuel consumption rate matrix is the same for all trip purposes, therefore, only 60 cells are needed.

Table D-2

Fuel Consumption Rate Estimates by Trip Length and Time
(Gallons per 100 miles)

Trip Length	Spring			Summer			Fall			Winter		
	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night
≤ 1	42.5	48.3	42.9	42.1	47.8	42.5	42.8	48.5	43.1	43.6	49.5	44.0
2-3	14.4	15.6	14.5	14.3	15.4	14.4	14.5	15.7	14.6	14.8	16.0	14.9
4-10	7.93	8.64	7.99	7.85	8.56	7.91	7.97	8.69	8.04	8.14	8.87	8.20
11-15	6.01	6.34	6.06	5.95	6.27	6.00	6.04	6.37	6.09	6.17	6.50	6.22
16+	4.83	5.08	4.87	4.78	5.03	4.82	4.85	5.11	4.89	4.95	5.21	4.99

Multiplying each cell of the above two matrices results in the following matrix of (total) fuel consumption by time and trip length category.

Table D-3

Fuel Consumption by Trip Length and Time
(Gallons x 10,000)

Trip Length	Spring			Summer			Fall			Winter		
	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night
≤ 1	74,205	77,280	40,411	62,013	64,864	35,572	67,153	71,634	36,505	70,414	77,022	37,532
2-3	74,952	79,716	42,267	69,283	73,920	41,040	83,712	78,548	43,435	69,634	78,080	38,218
4-10	137,776	168,367	85,069	130,215	160,517	83,806	132,310	166,343	81,155	117,134	152,324	69,978
11-15	53,711	71,084	35,754	47,005	62,148	32,400	42,800	57,330	27,862	41,567	58,500	26,665
16+	180,216	242,503	134,592	178,174	236,158	135,379	152,411	208,105	110,758	151,841	214,912	106,471
Total	520,860	638,950	338,093	486,690	597,607	328,197	478,386	581,960	299,715	450,590	580,838	278,864

Using these results, we find that the average (predicted) fuel consumption rates are:

- Spring 13.60 mpg
- Summer 13.99 mpg
- Fall 13.39 mpg
- Winter 12.90 mpg.

And the relative fuel consumption rates for winter and summer, and short and long trips are:

	≤ 3 Miles	16+
Winter	4.36 mpg	19.7 mpg
Summer	4.66 mpg	20.4 mpg

And the excess fuel consumed in winter due to lower temperatures is 1.02 billion gallons of gasoline.

The results are estimates based on the rudimentary model, which was developed for illustrative purposes. However, the validity of the model (and the approach) is verified by a separate analysis of seasonal fluctuations of fuel economy described below.

The Federal Highway Administration publishes on a regular monthly basis, gasoline sales and VMT estimates (the first in *Monthly Motor Gasoline Reported by States*, and the second in *Traffic Trends*). Using several years of this data (1976 and 1977), a gross mile per gallon figure can be calculated. The average mpg shown in the graph below is based on average vehicle miles per month and average gasoline sales per month figures. Also shown on the graph below is a rough average daily (for the month) temperature. This average daily temperature is based on the average daytime termperatures in five cities -- Madison, Boston, Atlanta, Los Angeles and Washington, D.C. The graph shows that there is good agreement in general between daytime temperature variation and average monthly fuel economy. However, there seems to be one serious anomaly in the data, Springtime mpg. However, the model explains the apparent anomaly, i.e., there is a high number of longer trips in Spring versus Fall so that average mpg is higher despite similar temperatures.

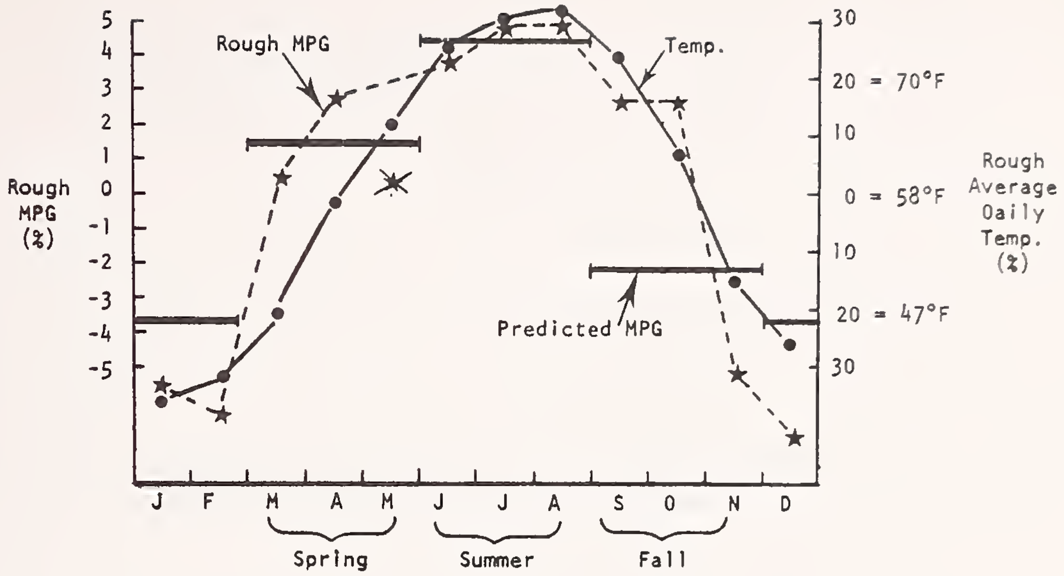


Figure D-1 MPG (Estimated and Calculated) and Temperature

In order to do the second example (the effect of reducing by 50 percent the number of commuter trips of one mile or less), one needs an additional matrix -- the matrix of VMT by trip purpose. Shown below is the matrix of trips and vehicle miles between home and work, based on the 1969-70 NPTS (See Appendix C for derivation).

Table D-4

Vehicle-Miles of Travel and Number of Trips by Trip Length and Time for Home-to-Work Trips

Trip Length	Spring			Summer			Fall			Winter		
	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night	Day	Commute	Night
≤ 1	202 151	734 550	163 122	258 193	672 504	150 112	277 208	721 540	160 120	315 236	820 615	183 137
2-3	317 792	825 2,062	184 460	318 795	828 2,070	184 460	352 880	917 2,292	204 510	343 857	892 2,230	198 495
4-10	593 3,854	1,544 10,036	343 2,229	590 3,835	1,537 9,990	341 2,216	608 3,952	1,583 10,289	351 2,281	578 3,757	1,505 9,782	334 2,171
11-15	205 2,562	534 6,675	119 1,487	184 2,300	479 5,987	107 1,337	170 2,125	442 5,525	99 1,237	179 2,237	465 5,812	104 1,300
16+	290 10,875	755 28,312	168 6,300	283 10,612	786 27,600	164 6,150	253 9,487	659 24,712	147 5,512	271 10,162	705 26,437	157 5,887
Total	1,607 18,234	4,392 47,635	977 10,598	1,633 17,735	4,252 46,151	946 10,275	1,660 16,652	4,332 43,358	961 9,660	1,686 17,249	4,387 44,876	976 9,990

This matrix shows that if 50 percent of the one mile or less trips were eliminated, the effect would be:

- 8 percent of commuter trips or 2.6 percent of all trips.
- 1.2 percent of commuter VMT or 0.5 percent of all VMT.
- 1.9 percent of all fuel consumption.

This result would have been obtained from a one-dimensional matrix using only trip length as a dimension. For the following equation, however, the complete matrix is needed: What would be the effects if all commuting trips of one mile or less, during daytime and commuting hours, were eliminated during spring and fall, and reduced by 50% during summer and winter; and if all commuting trips of 2 and 3 miles during daytime and commuting hours were reduced by 10%? The calculations show the following effects:

- 12% of all commuter trips or 3.9% of all trips.
- 1.1% of all commuter VMT or 0.5% of all VMT.
- 2.2% of all fuel consumption.

Derivation of the Fuel Consumption Matrix

The first step was to estimate the effect of temperature. A matrix of seasonal and temporal temperatures was developed. The daytime average temperature by season was estimated from data of the average monthly daytime (800 - 1800) hours) temperature for five sites -- Atlanta, Madison, Los Angeles, Boston and Washington, D.C. Rather than calculate exactly the day/night differential by season, a uniform 8 degree differential was estimated from examination of the monthly day and night average temperatures. The commuter time temperature was assumed to be half the day/night differential. This probably is too high for the morning and too low for the evening rush hours. The following matrix was produced.

Season	Day	Night	Commuter
Winter	40°F	32°F	36°F
Spring	65°	57°	61°
Summer	75°	67°	71°
Fall	60°	52°	56°

Next, the problem was to estimate the effect of these temperatures on fuel consumption. Initially, summer daytime was assigned a standardized fuel consumption rate of 100. Secondly, based on Scheffler and Niepoth (and others), a 1 percent change in mpg was assumed for every 10°F. Therefore the standardized fuel economy values for the matrix became:

Season	Day	Night	Commuter
Winter	96.5	95.7	96.1
Spring	99.0	98.2	98.6
Summer	100.0	99.2	99.6
Fall	98.5	97.7	98.1

The next step was to introduce the effect of trip length on the fuel consumption. Austin and Hellman (*Passenger Car Fuel Economy as Influenced by Trip Length*) gives

relative fuel consumption rates of 100 percent warmed up fuel economy. The following factors were applied to the above fuel consumption rates for the selected trip categories:

- ≤ 1 mile .25
- 2-3 miles .50
- 4-10 miles .67
- 11-15 miles .80
- 16+ miles .95.

This results in the following matrix:

≤ 1 mile

Season	Day	Night	Commuter
Winter	24.125	23.925	24.025
Spring	24.750	24.550	24.650
Summer	25.000	24.800	24.900
Fall	24.625	24.425	24.525

2-3 miles

Season	Day	Night	Commuter
Winter	48.25	47.85	48.05
Spring	49.50	49.10	49.30
Summer	50.00	49.60	49.80
Fall	49.25	48.85	49.05

4-10 miles

Season	Day	Night	Commuter
Winter	64.655	64.119	64.387
Spring	66.330	65.794	66.062
Summer	67.000	66.464	66.732
Fall	65.995	65.459	65.727

10-15 miles

Season	Day	Night	Commuter
Winter	77.2	76.56	76.88
Spring	79.2	78.56	78.88
Summer	80.0	79.36	79.68
Fall	78.8	78.16	78.48

16+ miles

Season	Day	Night	Commuter
Winter	91.675	90.915	91.295
Spring	94.050	93.290	93.670
Summer	95.000	94.240	94.620
Fall	93.575	92.815	93.195

The next step was to introduce the effect of speed. For this, three sources were used. The first source was our own analysis of NPTS data, which gave average speed for different trip length portions. The second source was the *Transportation and Traffic Engineering Handbook* for daily volume patterns and speed/volume relations. The final source was Evans and Herman's *Automobile Fuel Economy on Fixed Urban Driving Schedules*. The estimated average speeds per trip length category are:

- $\leq$ 1 mile 10 mph
- 2-3 miles 20 mph
- 4-10 miles 35 mph
- 11-15 miles 50 mph
- 16+ miles 65 mph.

Based roughly on material in the handbook, both day and night travel was assumed to be free flowing. Despite a doubling of the volume, commuter traffic speeds were assumed to be 80 percent of day and night speed. From Figure 1 in the Evans and Herman paper, an average fuel economy figure was interpolated. The very crude estimated values are:

- 10 mph 9.5 mpg
- 20 mph 14 mpg
- 35 mph 19 mpg
- 50 mph 21 mpg
- 65 mph 22 mpg.

The last value is probably unrealistically high.

The final fuel consumption rate matrix was calculated using basically these numbers. The following matrix is also shown in gallons per 100 miles, rather than miles per gallon, based on average trip speed.

Distance	Day and Night	Commuter
≤ 1 mile	10.53 gal/miles	11.90
2-3 miles	7.14	7.69
4-10 miles	5.26	5.71
11-15 miles	4.76	5.00
16+ miles	4.54	4.76

These figures are then multiplied by the inverse of the earlier factors which reflect the effect of temperature and trip length on miles per gallon, to arrive at the total fuel consumption matrix shown below in gallons per 100 miles.

≤ 1 mile

Season	Day	Night	Commuter
Winter	43.6	44.0	49.5
Spring	42.5	42.9	48.3
Summer	42.1	42.5	47.8
Fall	42.8	43.1	48.5

2-3 miles

Season	Day	Night	Commuter
Winter	14.8	14.9	16.0
Spring	14.4	14.5	15.6
Summer	14.3	14.4	15.4
Fall	14.5	14.6	15.7

4-10 miles

Season	Day	Night	Commuter
Winter	8.14	8.20	8.87
Spring	7.93	7.99	8.64
Summer	7.85	7.91	8.56
Fall	7.97	8.04	8.69

11-15 miles

Season	Day	Night	Commuter
Winter	6.17	6.22	6.50
Spring	6.01	6.06	6.34
Summer	5.95	6.00	6.27
Fall	6.04	6.09	6.37

16+ miles

Season	Day	Night	Commuter
Winter	4.95	4.99	5.21
Spring	4.83	4.87	5.08
Summer	4.78	4.82	5.03
Fall	4.85	4.89	5.11

This matrix shows a range of fuel economy rates is from 20.9 mpg (for summer, daytime and longer portion of trips) to 2 mpg (for winter commuter trips of one mile or less). It should be emphasized that the figures are intended to be illustrative, and not precise estimates.

APPENDIX E: REPORT OF NEW TECHNOLOGY

The purpose of this contract was to study travel and fuel consumption of personal motor vehicles.

A review and evaluation of data sources which could be used for calculating national estimates of automobile miles traveled were conducted, and a software method for organizing travel and fuel consumption data was developed and discussed.

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